

# DEMONSTRATION REPORT

Man-Portable Vector (MPV) EMI Sensor for UXO Contamination  
Assessment at Former  
Spencer Artillery Range, Tennessee

ESTCP Project MR-201158

APRIL 2013

Nicolas Lhomme  
**Black Tusk Geophysics, Inc.**

*This document has been cleared for public release*



<b>REPORT DOCUMENTATION PAGE</b>					<i>Form Approved OMB No. 0704-0188</i>	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.</b></p>						
<b>1. REPORT DATE (DD-MM-YYYY)</b> 16-04-2013		<b>2. REPORT TYPE</b> Final Technical Report			<b>3. DATES COVERED (From - To)</b> June 2012-April 2013	
<b>4. TITLE AND SUBTITLE</b> Demonstration Report for the MPV Study at Former Spencer Artillery Range, Tennessee: ESTCP MR-201158 Man Portable Vector EMI Sensor for UXO Contamination Assessment at Munitions Sites					<b>5a. CONTRACT NUMBER</b> W912HQ-12-C-0076	
					<b>5b. GRANT NUMBER</b>	
					<b>5c. PROGRAM ELEMENT NUMBER</b>	
					<b>5d. PROJECT NUMBER</b>	
<b>6. AUTHOR(S)</b> Dr. Nicolas Lhomme, Black Tusk Geophysics, Inc.					<b>5e. TASK NUMBER</b>	
					<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Black Tusk Geophysics, Inc. 112A-2386 East Mall Vancouver, BC V6T 1Z3 Canada					<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Environmental Security Technology Certification Program 901 North Stuart Street, Suite 303 Arlington, VA 22203-1821					<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
					<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Approved for public release; distribution is unlimited						
<b>13. SUPPLEMENTARY NOTES</b>						
<b>14. ABSTRACT</b> The Man-Portable Vector electromagnetic induction sensor is a new-generation instrument designed to extend classification of unexploded ordnance (UXO) to sites where vegetation or terrain limit access to vehicle-based advanced geophysical platforms. The MPV participated in the June 2012 ESTCP live-site demonstration at Spencer Range, Tennessee, where detection and classification were tested. The detection survey covered 1.3 acre in open field, where all targets were detected and 300 anomalies were investigated in cued mode. All targets were correctly classified with 90% clutter rejection. Portable systems were also tested in a forested area where cued interrogation data were collected over 700 flags using the beacon positioning technology. Classification correctly identified 99% of the munitions while rejecting 85% of the clutter. The survey was completed in 12 days with an average production rate of 0.5 acre per day in detection mode and 125 anomalies per day in cued mode. All demonstration objectives were met. The MPV technology will be involved in further ESTCP demonstrations in 2013.						
<b>15. SUBJECT TERMS</b> Man Portable Vector Sensor, Electromagnetic Induction Sensor, UXO, Spencer Range, Live-Site Demonstration, Detection, Classification, Geophysical Inversion						
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>		<b>18. NUMBER OF PAGES</b>	
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE Uu	UU		<b>19a. NAME OF RESPONSIBLE PERSON</b> Dr. Herb Nelson	
					<b>19b. TELEPHONE NUMBER (Include area code)</b> 703-696-8726	

## Table of Contents

List of Figures .....	iii
List of Tables .....	iv
Acronyms .....	iv
ACKNOWLEDGEMENTS .....	v
EXECUTIVE SUMMARY .....	vi
1.0 INTRODUCTION .....	1
2.0 TECHNOLOGY .....	1
2.1 MPV TECHNOLOGY DESCRIPTION .....	1
2.2 MPV TECHNOLOGY DEVELOPMENT .....	3
2.3 ADVANTAGES AND LIMITATIONS OF THE MPV TECHNOLOGY .....	4
3.0 PERFORMANCE OBJECTIVES .....	5
3.1 OBJECTIVE: SPATIAL COVERAGE FOR DETECTION .....	6
3.2 OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION TESTS .....	6
3.3 OBJECTIVE: DETECTION OF ALL MUNITIONS OF INTEREST .....	7
3.4 OBJECTIVE: PRODUCTION RATE .....	7
3.5 OBJECTIVE: EASE OF USE .....	7
3.6 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION .....	8
3.7 OBJECTIVE: MINIMUM NUMBER OF FLAGS THAT CANNOT BE ANALYZED .....	8
3.8 OBJECTIVE: LOCATION AND DEPTH ACCURACY FOR TOI .....	9
4.0 SITE DESCRIPTION .....	10
4.1 SITE SELECTION .....	10
4.2 SITE HISTORY .....	11
4.3 MUNITIONS CONTAMINATION .....	11
4.4 SITE CONFIGURATION .....	11
5.0 TEST DESIGN .....	12
5.1 DEMONSTRATION SCHEDULE .....	12
5.2 SYSTEM SPECIFICATION .....	12
5.3 CALIBRATION ACTIVITIES .....	13
5.4 DATA COLLECTION PROCEDURES .....	15
6.0 DATA ANALYSIS PLAN .....	18
6.1 PREPROCESSING .....	18
6.2 TARGET SELECTION FOR DETECTION .....	18
6.3 PARAMETER ESTIMATION .....	18
6.4 TRAINING .....	19

6.5	CLASSIFICATION .....	19
7.0	PERFORMANCE ASSESSMENT .....	22
7.1	IVS repeatability .....	22
7.2	Classification performance.....	23
7.3	Location and depth prediction.....	26
7.4	Field survey statistics and production rate .....	26
8.0	COST ASSESSMENT.....	28
8.1	COST MODEL .....	28
8.2	COST DRIVERS .....	30
8.3	COST BENEFIT .....	30
9.0	IMPLEMENTATION ISSUES .....	31
10.0	REFERENCES .....	32
	Appendix A: Health and Safety Plan (HASP) .....	33
	Appendix B: Points of Contact .....	35
	Appendix C: Detection range with MPV survey .....	36
	Appendix D: Root Cause Analysis for Missed Detection .....	38
	1. Background.....	38
	2. Target detection process .....	39
	3. Missed targets .....	40
	4. Improving quality control .....	41
	5. Conclusion .....	41
	Appendix E: Field notes.....	42
	Appendix F: Classification Decision Memorandum.....	44
	1. Unclassifiable anomalies .....	44
	2. Classification approach and features .....	46
	3. Training data selection.....	46
	4. Parameters and thresholds.....	48
	5. Stop-dig decision .....	49

## List of Figures

Figure 1: The MPV as deployed at Spencer Range, TN in June 2012. ....	1
Figure 2: The MPV detection display window in dynamic data collection mode. ....	2
Figure 3: Aerial photograph of demonstration site. ....	10
Figure 4: Data collection over test pit. Reference TOI were placed in empty hole and surveyed in cued mode. ....	13
Figure 5: Background signal for static data at Spencer Range (field and IVS). ....	14
Figure 6: Cued survey pattern with five points centered on marked target location. ....	15
Figure 7: Picture of dynamic survey with MPV. ....	15
Figure 8: Typical target response when the MPV head is placed directly above a buried target. ....	16
Figure 9: Polarizabilities for ranked dig list at classification stage 2. ....	20
Figure 10: Format of prioritized dig list to be submitted to ESTCP Program Office. ....	21
Figure 11: Polarizabilities on IVS lane: (A) 75 mm, (B) 37 mm, (C) Shotput and (D) ISO2. ....	22
Figure 12: Map of multiple dynamic passes on the IVS. ....	23
Figure 13: Polarizabilities of IVS items from dynamic data. (A) ISO2, (B) 37 mm, (C) 75 mm and (D) shotput. ....	23
Figure 14: ROC curves for the MPV surveys at Spencer Range. ....	24
Figure 15: Target parameters for SR-2355, which was missed during classification. ....	25
Figure 16: Comparison of predicted location and depth with ground truth. ....	26
Figure 17: Graphical summary of daily data collection production rate. ....	27
Figure 18: Location of medical facilities: river Park in NE and Surgical Care in E. ....	34
Figure 19: Regional map with Spencer Range location relative to McMinnville. ....	34
Figure 20: SNR cross section for different target offset and depth relative to side receiver. ....	36
Figure 21: 37 mm target in vertical orientation. ....	37
Figure 22: SNR cross section for 105 mm projectile; (A) Horizontal; (B) Vertical. ....	37
Figure 23: Survey in quiet background (Beale IVS) over 37 mm (A) and 105mm (B). ....	37
Figure 24: Detection map of Spencer dynamic area; MPV total field data at 1.4 ms. The survey boundary is indicated with the green line. ....	38
Figure 26: Predicted response for 37 mm projectile: horizontal (A); vertical (B). ....	39
Figure 25: Recovered polarizabilities for a 37 mm projectile based on inversion of static (grey lines) and dynamic (colors) data. ....	39
Figure 27: Distribution of background response. ....	39
Figure 29: Detection map for the 2 <sup>nd</sup> missed anomaly (A, marker #271 on the green survey boundary) and 3 <sup>rd</sup> one (B, secondary anomaly 1 m to the North of marker #6). ....	40
Figure 28: Detection map near the 1 <sup>st</sup> missed target (360). The survey boundary is indicated with a green line. ....	40
Figure 30: Re-examination of the 3 <sup>rd</sup> missed target; Data for Z (A) and Y (B) component receivers. ....	41
Figure 31: Distribution of target size and decay parameters relative to reference UXOs. ....	44
Figure 32: Failed anomaly on edge of survey. ....	45
Figure 33: Failed anomaly on edge of survey. ....	45
Figure 34: Failed anomaly on edge of survey. ....	46
Figure 35: Cluster analysis of model parameters. ....	47
Figure 36: Decision statistic (A) based on "recognized UXO" (red dots) and expected ROC curve (B). ....	49

## List of Tables

Table 1: Performance Objectives.....	5
Table 2: Demonstration steps.....	12
Table 3: Targets with difference in caliber.....	24
Table 4: Cost model for MPV demonstration at Spencer Range.....	28
Table 5: Points of Contact for the MPV Demonstration.....	35
Table 6: Training data summary.....	47

## Acronyms

AHRS	Attitude and Heading Reference System
BUD	Berkeley UXO Discriminator
CFR	Code of Federal Regulations
cm	Centimeter
CO	Colorado
CRREL	Cold Regions Research and Engineering Laboratory (ERDC)
DAQ	Data Acquisition System
DGM	Digital Geophysical Mapping
EMI	Electromagnetic Induction
ERDC	Engineering Research and Development Center
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning Systems
HASP	Health and Safety Plan
IDA	Institute for Defense Analyses
IVS	Instrument Verification Strip
m	Meter
mm	Millimeter
MPV	Man Portable Vector
ms	millisecond
MR	Munitions Response
NH	New Hampshire
NSMS	Normalized Surface Magnetic Source
OR	Oregon
PI	Principal Investigator
POC	Points of Contact
RTK	Real-time Kinematic
s	Second
SERDP	Strategic Environmental Research and Development Program
SNR	Signal to Noise Ratio
SVM	Support Vector Machine
TEMTADS	Time Domain Electromagnetic Towed Array Detection System
UXO	Unexploded Ordnance
YPG	Yuma Proving Ground

## ACKNOWLEDGEMENTS

The MPV demonstration at former Spencer Range, Tennessee was funded by the Environmental Security Technology Certification Program project MR-201158. Initial sensor development and testing was supported by *Strategic Environmental Research and Development Program* project MM-1443. The sensor was maintained and prepared for the demonstration by David George of G&G Sciences, who fabricated the prototype in the ESTCP project MR-201005.

The field deployment involved Jon Jacobson, James Gayer and the P.I. Nicolas Lhomme (all with Sky Research at the time; the P.I. is now with Black Tusk Geophysics, Inc.). The P.I. was the main performer for all other tasks, except for the review of inversion results for cued data that was done by Jon Jacobson. Erik Russell assisted with project coordination.

## EXECUTIVE SUMMARY

This document reports on the ESTCP live-site demonstration that was performed with the Man-Portable Vector (MPV) sensor at the Spencer Artillery Range near Spencer, Tennessee in June 2012. This study encompasses the data collection survey, data processing and classification and performance analysis.

The MPV technology is a handheld sensor for munitions detection and classification. Its form factor was specifically designed for sites such as Spencer Range, where vegetation or terrain limits access to vehicle-based platforms. The MPV is an electromagnetic induction (EMI) sensor that comprises of a 50-centimeter diameter transmitter and an array of three-dimensional receivers. The MPV can be deployed with multiple positioning systems depending on the environment. Standard GPS technology can be used under open sky. Under thick canopy GPS signal is disturbed and therefore a specific portable local positioning system was developed. Its principle is based on locating the MPV transmitter, which acts similar to a beacon, and is not affected by natural obstacles. A survey can therefore be performed in forested and rugged environments. The MPV can be employed for detection survey and for cued interrogation, in which high quality data are acquired near a target to achieve the best classification. The MPV technology was validated at Yuma Proving Ground, Arizona UXO Standardized Test Site in October 2010, where 90% of targets within 1-m depth were detected and correctly classified. The sensor was subsequently demonstrated at former Camp Beale, California in June 2011 along other portable systems in a treed environment, achieving 100% correct classification.

The Spencer study was designed to test portable technologies along with vehicular systems. A forested area contained 700 flags that were characterized by cued interrogation with the portable sensors, whereas a 1.3-acre open area hosting approximately 300 potential targets was tested with most systems doing a detection survey followed with cued interrogation of the detected anomalies. A testing lane and empty pit were set up for calibrating the MPV over known targets every day. The MPV was deployed with one experienced and one new field operator, and one on-site data processor. Dynamic detection data were collected in 2.5 days; data were mapped and interpreted to select anomalies that were validated by the ESTCP for further characterization. The 1000 anomalies of interest were acquired over 8 days. Some days as many as 150 anomalies were visited. The entire survey was completed without any technical interruption. Data were reviewed and quality-controlled on-site; after collection, pre-processed data were distributed to other ESTCP analysts in support of the classification study. Our study was divided in two parts. For the forested area, cued data analysis allowed 99% correct classification of buried munitions while rejecting 85% of the clutter. The dynamic area was treated using dynamic data as a pre-screener to classify half of the anomalies, and turning to cued data for the more ambiguous anomalies. All targets of interest were found while rejecting 90% of the clutter, which indicates a strong potential for significantly reducing the number of anomalies that need to be investigated in cued mode for future studies. All demonstration objectives were successfully met.

The MPV has now been demonstrated at one proving ground and two live sites where classification has been successful and field productivity has improved. The site conditions posed no particular difficulties for a handheld technology like the MPV; other sites will be visited to further establish the performance, limitations, optimum usage and costs of the technology. The MPV is scheduled to be deployed and tested at several sites through year 2013 as part of the ESTCP ongoing live-site demonstration program.



## 1.0 INTRODUCTION

The demonstration at former Spencer Artillery Range (Spencer) is one in the series of Environmental Security Technology Certification Program (ESTCP) demonstrations of classification technologies for Munitions Response (MR). This demonstration is designed to investigate the evolving classification methodology at a site that is partially wooded with a mix of munitions types. This project proposes to demonstrate detection and classification with the Man Portable Vector (MPV) sensor. The MPV is an electromagnetic induction (EMI) sensor that was designed to extend advanced discrimination capabilities to sites with challenging surveying conditions and, thus allow for advanced discrimination to be applied at most human trafficable land locations at moderate cost. The system is deployed in dynamic search to test detection capabilities and in cued interrogation, where a series of detected EMI anomalies are investigated for classification by collecting multiple static soundings.

In the following document, we shall try to abide by the following definitions. An anomaly is a signal or a location where a sensor detected a peak in the EMI data - in that sense it is correct to refer to inverted or classified anomalies. The flag is the marked location where the detection survey predicted the anomaly to be located. Each flag is associated with a label that indicates the site specific identity number. A target of interest (TOI) is an ammunition or a seeded simulant such as an ISO cylinder. Target picking is the action of selecting anomalies of interest.

## 2.0 TECHNOLOGY

The MPV technology is based on electromagnetic induction sensing using one transmitter coil and multiple vector receivers in a handheld form factor. The sensor presented in this study is the second-generation prototype MPV.

### 2.1 MPV TECHNOLOGY DESCRIPTION

#### 2.1.1 Electromagnetic sensor

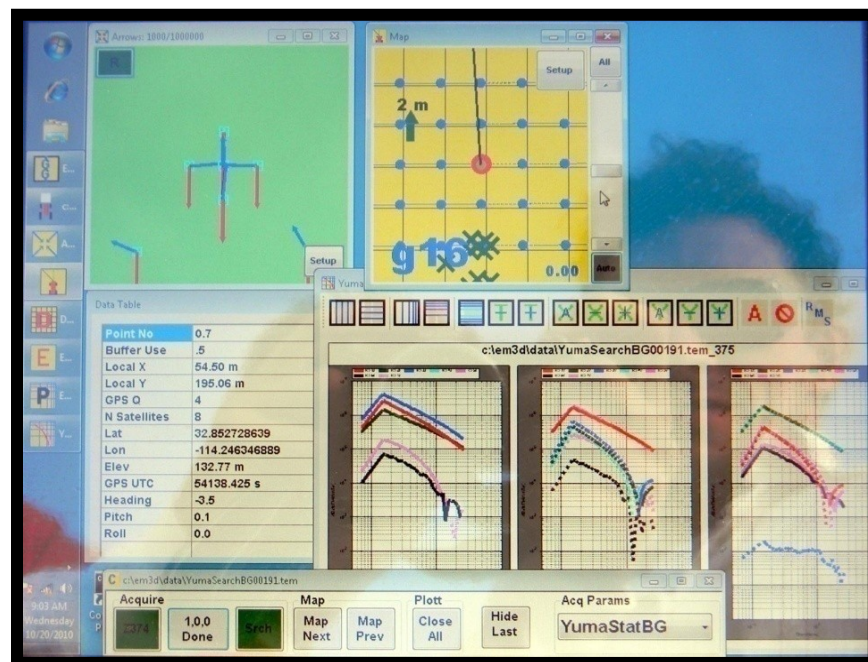


Figure 1: The MPV as deployed at Spencer Range, TN in June 2012.

It includes a sensor head with one transmitter loop and five 3D receiver cubes inside a transparent casing, a touch-screen display to control survey parameters and acquisition (right inset), and a DAQ with batteries mounted on a backpack frame carried by the second operator (left inset). The MPV can use two positioning systems: GPS and AHRS for open field survey; a beacon boom in forest or steep terrain.

The MPV is a handheld sensor with wide-band, time-domain, EMI technology. The sensor head is composed of a single transmitter coil and an array of five receiver units that measure all three components of the EM field (Figure 1). This second-generation MPV is specifically designed to (1) be man portable and therefore easy to deploy, maneuver and adapt to a survey environment, and (2) acquire data that is suitable for discriminating unexploded ordnance (UXO) from non-UXO targets. The MPV head is a 50-centimeter (cm) diameter transparent disk. The transmitter coil is wound around the disk and intermittently illuminates the subsurface. Five receiver units (cubes) measure the three orthogonal components of the transient secondary EM field decay with three air-induction 8-cm square coils – having multiple receivers generally improves the recovery of target parameters for classification (Gasperikova et al., 2007).

The MPV is a programmable instrument. The duration of the excitation and time decay recording can be adjusted to accommodate the specific needs of target detection and classification. The detection survey consists of a full-coverage sweep where dynamic data are collected for digital geophysical mapping (DGM). Fast EMI transmit-receive cycles are applied so that the sensor can continuously move (e.g., 1 millisecond [ms] time decay, similar to Geonics EM-61). The quality of detection data may not always be sufficient for target classification. In such case a target is reacquired in cued interrogation, where data quality is to be maximized. The sensor is static to stack the recorded signal and reduce noise. Longer EMI cycles are applied to capture variations in time decay rates (e.g., 25 milliseconds (ms), similar to Geonics EM-63). This late-time information has been shown to improve distinction between intact ordnance and thinner walled shrapnel and cultural debris (Billings et al., 2007).



**Figure 2: The MPV detection display window in dynamic data collection mode.**

The top left panel indicates with arrows the direction of the nearest compact metallic object relative to the MPV receiver cubes and directs the operator to the target (here the MPV sits atop the target). The top middle panel shows a field map with the MPV location (red dot) and azimuth (black line), potential target locations (blue dots), and cued interrogation soundings (green crosses). The middle left panel provides feedback on positioning sensors. The bottom panel has the data acquisition options for simple one-button-touch operation.

The MPV is a handheld sensor. The sensor head weights approximately 13 pounds and the backpack-mounted data acquisition (DAQ) and batteries weight 35 pounds. Existing sensors with multiple time channel measurement capabilities (e.g., Berkeley UXO Discriminator [BUD], Geonics EM63, Time Domain EM Towed Array Detection System [TEMTADS]) are required to be mounted on a cart platform due to the size and weight of the multiple coils of wire required for the transmitters and receivers.

The MPV user interface has real-time data monitoring capabilities. The recorded data can be displayed to verify data quality and detect potential disturbances such as presence of magnetic soil or a damaged receiver. The past and present sensor location is displayed on a map along with preset survey points to verify spatial coverage and global location. A target detection and location tool indicates the origin of measured EMI fields with arrows (the so-called “dancing arrows” in top left corner of Figure 2). These features assist the field operator in efficient data collection, so that detection and discrimination data can be collected as part of the same survey, thus limiting the need to revisit a flag for further characterization.

### **2.1.1 Geolocation**

The MPV accommodates different positioning systems depending on site conditions and survey needs. For detection mapping Global Positioning System (GPS) combined with Attitude and Heading Reference System (AHRS) provide navigation and positioning in open field or sparse forest. Under dense canopy, sensor location can be estimated with a cotton thread and spool measuring distance along track.

For inversion and classification, target parameters are best recovered when a target is illuminated from multiple directions to recover its transverse polarizabilities. When deployed with a single transmitter loop the MPV can achieve that effect by acquiring soundings at multiple locations – usually five – around the anomaly. This technique imposes stringent positioning constraints for reliable classification (Bell, 2005). A custom positioning system was designed to meet these requirements in all environments without the line-of-sight limitations of GPS and roving lasers. The “beacon” system (San Filippo et al., 2007) consists of locating the origin of the primary field generated by the active MPV transmitter coil, acting as a beacon, with a pair of EMI receivers that are rigidly attached to a portable beam (Figure 1). The beam is placed on the ground and remains at the same location during cued interrogation of an anomaly, like a base station, to derive relative sensor location. The method meets accuracy requirements for target classification (Lhomme et al., 2011) with 1-2 cm and 1-2 degrees accuracy for position and orientation – similar to GPS – out to distances of 3-4 meters (m). The beacon has been utilized at all field demonstrations to date.

## **2.2 MPV TECHNOLOGY DEVELOPMENT**

The project was initiated in 2005 under the Strategic Environmental Research and Development Program (SERDP) MM-1443. The project was led by Drs. Kevin O’Neill and Benjamin Barrowes with the Cold Regions Research and Engineering Laboratory of the Engineering Research and Development Center (CRREL, ERDC) in Dartmouth, New Hampshire (NH). The first MPV prototype was built in 2005-2006 with David George of G&G Sciences, Grand Junction, Colorado (CO). It was tested in 2007 at ERDC in a laboratory setting. Data analysis showed that stable target parameters could be retrieved and used for UXO classification.

The SERDP project was first extended in 2008 to continue testing. Field trials were done at a test plot with static and dynamic acquisition mode over buried targets. Stable target parameters were recovered. Effect of magnetic soil on EMI sensors was investigated. Adverse soil effects could be defeated owing to the MPV's array structure. The positioning system – ArcSecond laser ranger – proved to be impractical for field application due to line-of-sight requirement for all three rovers and tedious calibration. The SERDP project was extended to test an alternative positioning system based on the beacon concept and prepare modification of the original MPV prototype for extensive field deployments. The sensor head was redesigned with lighter materials and a smaller head diameter to reduce weight and improve maneuverability while maintaining its expected performance (Lhomme, 2011b). Receivers were placed inside transmitter coil to reduce fragility; transparent material was employed to see through the unit.

Funding was obtained in 2010 in ESCTP MR-201005 to continue developing the MPV and performing field demonstrations. The MPV fabrication was completed. The MPV was successfully demonstrated at YPG UXO test site in October 2010 and at former Camp Beale in June 2011. High detection and classification rates were achieved.

### **2.3 ADVANTAGES AND LIMITATIONS OF THE MPV TECHNOLOGY**

The MPV is the only available handheld sensor that can acquire multi-static, multi-component data on a wide and programmable time range. The MPV offers several key benefits:

- Hand-held form factor: The MPV can be deployed at sites where terrain and vegetation preclude use of heavier, cart-based systems. Portability can improve productivity in rough terrain. The system is easy packable and transportable;
- Five receivers simultaneously record three orthogonal components of EM field with near-perfect relative positioning among receivers. Multi-component, multi-axis design reduces number of soundings for target characterization (Barrowes et al., 2007) and relaxes positional accuracy (Grzegorzczak et al., 2009);
- Magnetic soil can be detected and defeated: The geometric arrangement of receivers and the wide-band time range offer potential for identifying and neutralizing the effect of magnetic soil through techniques developed in SERDP MM-1414 and MM-1573.
- Fully programmable through field display: Graphical field-user interface controls acquisition parameters such as transmitter waveform characteristics, duration of excitation, number of measurement cycles, stacking and recorded time channels.
- Highly stable EMI components: Responses are directly predictable using standard EMI theory. Field tests verified that MPV components had imperceptible measurement drift and were largely insensitive to survey conditions.
- Small target characterization: Small items have localized, rapidly-varying spatial response. Voltage in an air induction receiver coil is an average of a target scattered field through the face of the loop. Therefore, large receivers tend to “smear out” signals. The MPV's 8 cm square coils are typically smaller than most multi-channel sensors and thus better suited to detecting and sampling signals from small targets.

Portability has limitations: with a single transmitter, multiple soundings must be collected to characterize a target. Therefore the MPV requires (1) an accurate positioning system for cued interrogation and (2) manual intervention to move the sensor, which reduces productivity relative to a multi-transmitter platform for which a single sounding is often sufficient.

### 3.0 PERFORMANCE OBJECTIVES

This project includes data collection in dynamic detection and cued interrogation, data analysis and user feedback for evaluation of the MPV technology. The specific objectives for each stage are detailed in Table 1. The first four objectives are mostly intrinsic to the quality of the sensor and of the deployment method. The data were analyzed by the demonstrator and by other ESTCP partners.

**Table 1: Performance Objectives.**

Performance Objective	Metric	Data Required	Success Criteria	Results
<b>Data Collection Objectives</b>				
Spatial coverage in detection survey	Extended footprint coverage	<ul style="list-style-type: none"> <li>• Mapped survey data</li> </ul>	95% coverage	95%
Repeatability on IVS	Amplitude of EM anomaly Amplitude of polarizabilities	<ul style="list-style-type: none"> <li>• IVS survey data</li> </ul>	Detection amplitude and inferred size within a factor 3 of mean value	Detection: Amplitude within factor 1.5 Cued: Size within factor 1.1
Detection of all targets of interest	Percent detected of seeded TOI	<ul style="list-style-type: none"> <li>• Location of seeded TOI</li> <li>• Flag list</li> </ul>	95% within 0.3 m depth 90% from 0.3-1 m depth	100% of seeds were detectable 3 seeds missed
Production rate	Daily number of cued interrogations Pre-processing time	<ul style="list-style-type: none"> <li>• Log of field work and data pre-processing time</li> </ul>	100 flags Pre-proc. time: 3 min per target	Mean: 125 per day (Max 150)
Ease of use		<ul style="list-style-type: none"> <li>• Feedback from operators/trainees on usability and training time</li> </ul>		Quick learning Detection: ergonomics better for tall people
<b>Analysis and Classification Objectives</b>				
Maximize correct classification	Number of TOI retained and rate of clutter rejected	<ul style="list-style-type: none"> <li>• Ranked dig list</li> <li>• Scoring reports by IDA</li> </ul>	Retain at least 95% TOI False alarms reduction by at least 50%	TOI correctly classified: 99% (forest), 100%(dynamic) 85% FAR reduction
Minimize number of flags that cannot be analyzed	Number of “Cannot Analyze” in classification	<ul style="list-style-type: none"> <li>• Ranked dig list</li> </ul>	Reliable parameters for at least 95% flags	Over 99% flags with reliable parameters
Location and depth accuracy for TOI	Mean error and standard deviation in depth, northing and easting	<ul style="list-style-type: none"> <li>• Location of validated within 0.05 m</li> <li>• Predicted location</li> </ul>	$\sigma\Delta Z < 0.10$ m $\sigma\Delta N$ and $\sigma\Delta E < 0.30$ m	$\sigma\Delta Z = 0.05$ m $\sigma\Delta N$ and $\sigma\Delta E = 0.20$ m

### **3.1 OBJECTIVE: SPATIAL COVERAGE FOR DETECTION**

Dynamic detection survey should cover a maximum of the area of interest so that all detectable targets are illuminated. Targets are detectable if the transmitted field is sufficiently strong to reach the target and if the measured target response is sufficiently strong in return to exceed a given threshold. Simulations suggest that there is negligible loss of detect-ability when a target is located 10 cm to the side of the MPV (Appendix C). We can therefore assume a 70 cm effective diameter footprint for the MPV sensor head.

#### **3.1.1 Metric**

The survey footprint is compared with dynamic survey surface area. In practice the geographical coordinates of MPV receivers are binned in 20-cm square cells. The ratio of the number of non-empty cells and the number of cells in the survey area provides the rate of coverage.

#### **3.1.2 Data requirements**

The geographic coordinates of the survey perimeter and the survey track are utilized.

#### **3.1.3 Success criterion and result**

The objective of 95% spatial coverage was attained.

### **3.2 OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION TESTS**

Reliability of survey data depends on stability of survey equipment. The IVS was tested twice daily on the Instrument Verification Strip (IVS) in detection mode during the detection survey. Cued interrogation of IVS targets was done during the entire demonstration.

#### **3.2.1 Metrics**

The amplitude of the MPV data and that of the target parameters span multiple orders of magnitude. For instance, the raw amplitude of a target response doubles for every 5 cm increment in target depth; there is a factor 10 between the amplitude of the polarizabilities of a 37 mm and a 75 mm projectile, and their time decays span 5 orders of magnitude over a 0.1-25 ms time range. Therefore analyses are often performed on the logarithmic values of these quantities. The metric for detection is the amplitude of the maximum target response, defined as the norm of the total field on a cube. The metric for cued interrogation is target size, here defined as the norm of the polarizability components at early time.

#### **3.2.2 Data requirements**

The IVS survey data were recorded and analyzed.

#### **3.2.3 Success criterion and result**

This objective was for the target response amplitude and the size factor to remain within a factor 3 of the mean value. In practice we achieved a repeatability within a factor 1.5 for detection data and 1.1 for the polarizabilities inferred from cued data (Section 7.1).

### **3.3 OBJECTIVE: DETECTION OF ALL MUNITIONS OF INTEREST**

Target detection depends on signal intensity, spatial coverage and the target picking method.

#### **3.3.1 Metric**

The metric for this objective is the percentage of flags for which survey data exceed the detection threshold.

#### **3.3.2 Data requirements**

Survey data were recorded.

#### **3.3.3 Success criterion and result**

The objective was considered to be met if detection rate exceeds 95% within 0.3-m depth and 90% from 0.3-1 m for all TOI for which burial depth is less than the minimum of 1 meter and 10 times the target caliber. All targets were detectable. However, three seeding items were initially not selected because two laid right at the survey boundary and one target was merged with another pick as part of a wide anomaly. A root cause analysis memorandum was submitted to review the procedure (included in Appendix D).

### **3.4 OBJECTIVE: PRODUCTION RATE**

Cued interrogation and data analysis should be quicker than excavating every potential target. Here we only consider data collection and pre-processing. The latter task involves preparing data for distribution to analysts and includes: digitizing field notes, consolidating all soundings per flag, inferring sensor position with the beacon and merging location, removing background and normalizing by transmitter current.

#### **3.4.1 Metric**

The metrics for this objective are the mean daily survey rate and the mean pre-processing time per flag.

#### **3.4.2 Data requirements**

The number of surveyed flags and pre-processing time were recorded every day.

#### **3.4.3 Success criterion and result**

The objective of 100 flags per day was exceeded with a mean of 125 flags and two days with 150 flags. Originally pre-processing time was near the objective of 3 minutes per flag. However, we later found occasional drift with the beacon boom compass that forced a re-analysis of the beacon positions and increased the overall time to 5 minutes.

### **3.5 OBJECTIVE: EASE OF USE**

This objective is qualitative. One new field personnel was involved in the data collection. The crew was provided with initial technical material for familiarization with the technology. The mode of operation was explained and data collection was explained and demonstrated first on the IVS and training pit with dynamic and cued interrogation. By the time the IVS and pit were surveyed, the crew was able to collect cued data over simple anomalies and recognize more

complex situations, e.g., offset targets, and ask for confirmation of the appropriate task to perform. Overall the experienced field technician and the trainee collected equal amount of data with similar quality and productivity. Overall data quality was satisfactory - spatial coverage met the objective, few recollects - which suggests a successful technology transfer.

In terms of ergonomics we found that the sensor handle was better designed for tall people, who were also at greater ease for sweeping the sensor head across track in detection survey.

### **3.6 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION**

This is the most important objective of the demonstration: all shallow munitions should be recommended for excavation after geophysical inversion and a maximum of clutter should be dismissed. This objective requires that sufficient, high-quality data are collected, and that the ensuing data analysis, inversion and statistical classification process recognizes the presence of munitions. The prioritized dig list indicates an estimate of target type and a stop dig point.

#### **3.6.1 Metric**

The metric for this objective is the rate of TOI that are recognized as such and the rate of clutter left after the stop dig point.

#### **3.6.2 Data requirements**

Ranked dig lists were submitted to the ESTCP Program Office for scoring by the Institute for Defense Analyses (IDA).

#### **3.6.3 Success criterion and result**

The objective was to identify at least 95% of the UXO with at least 50% clutter rejection. For the forested area we achieved 99% correct classification with 85% clutter rejection, missing one ISO in a fragment pit among four other pieces. The dynamic area was processed in two stages: approximately half of the anomalies were successfully classified using dynamic data, while the remaining ones were classified using cued data. We found 100% of the TOI and rejected over 85% of the clutter (details in Section 7.2).

### **3.7 OBJECTIVE: MINIMUM NUMBER OF FLAGS THAT CANNOT BE ANALYZED**

Some flags may not be classified due to insufficiently informative data or inadequate data processing. The former is a measure of instrument performance and field practices; the latter is a measure of data analysis quality.

#### **3.7.1 Metric**

The metric for this objective is the number of flags that cannot be analyzed by our method, and the intersection of all dig lists among all analysts.

#### **3.7.2 Data requirements**

Each analyst submitted their dig list for scoring by IDA.



### **3.7.3 Success criterion and result evaluation and results**

The objective to classify at least 95% of the flags with the MPV depth range of investigation was exceeded with over 99%. Only three flags could not be classified because their corresponding anomalies were offset by over 50 cm and the field operator did not extend the survey pattern to fully cover the anomaly (Details in Appendix F.1). These flags were failed, though technically they could have been classified as empty holes.

## **3.8 OBJECTIVE: LOCATION AND DEPTH ACCURACY FOR TOI**

Correct target classification relies on the capability to extract accurate target parameters. Accurately locating potential TOI is important for safe and efficient site remediation.

### **3.8.1 Metric**

The metric is the difference between observed and predicted depth and geographic location.

### **3.8.2 Data requirements**

Predicted location and depth are recorded among target parameters and compared to ground-truth validation measurements.

This objective requires accurate ground truth. This condition may be challenging given that flags may have been removed between the interrogation and excavation events, and flags might have also been misplaced and not lay sufficiently close to the anomaly of interest.

### **3.8.3 Success criterion and result**

Depth should generally be predicted within 0.10 m and geographic location within 0.30 m (the typical radius of an excavation hole). The standard deviation for the difference between the predicted and observed depth and location are 0.05 m and 0.20 m, respectively, and the means are close to zero.

## 4.0 SITE DESCRIPTION

The site description material reproduced in this section is taken from the ESTCP Demonstration Plan for Spencer Range (Draft 3), where reference to additional material can be found. The former Spencer Artillery Range is a 30,618 acre site located near Spencer, Tennessee. The demonstration was conducted in a portion of the Munitions Response Site (MRS) 1. An aerial photo of the demonstration area is shown in Figure 3.

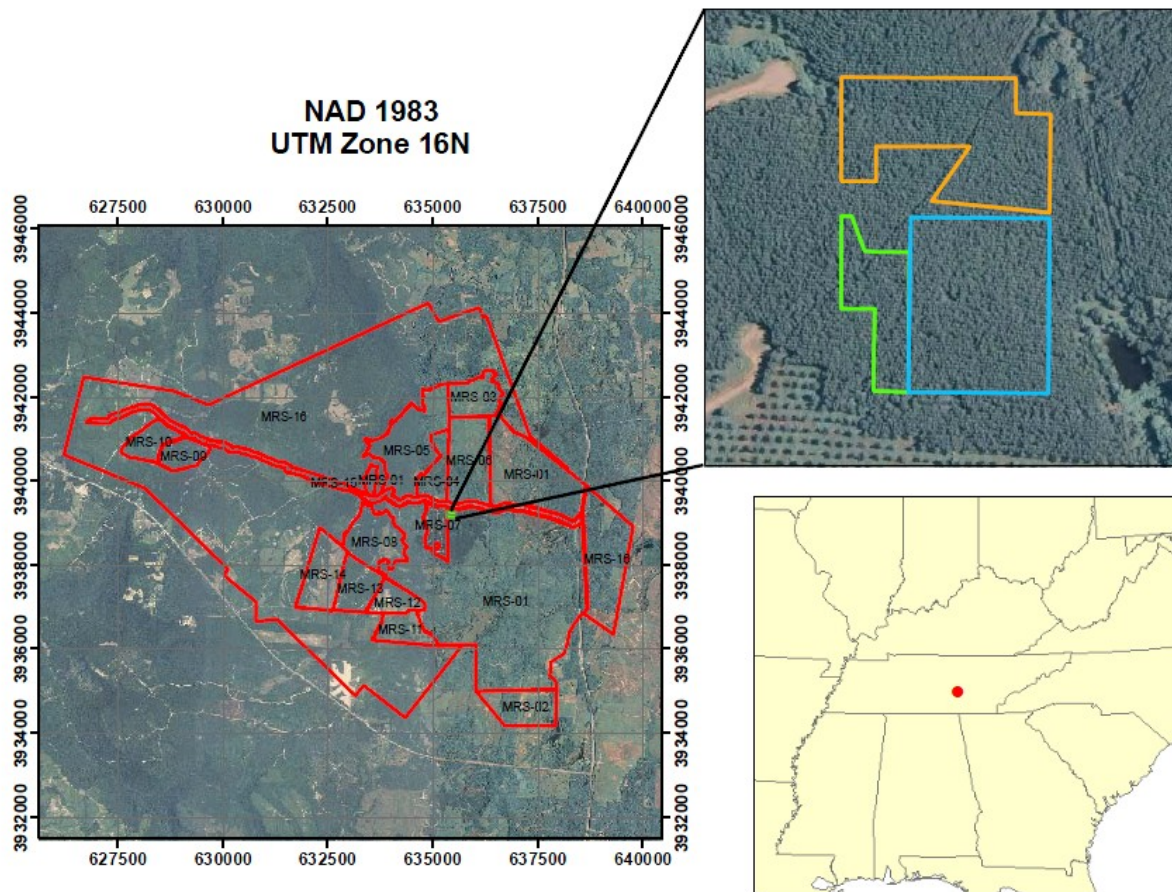


Figure 3: Aerial photograph of demonstration site.

In the upper right panel, orange contour indicates the forest survey area (portable systems only), green line limits dynamic area where all sensors were deployed in dynamic and static mode (except BUD) and while blue area was set for the MetalMappers only.

## 4.1 SITE SELECTION

This site was chosen as the next in a series of sites for demonstration of the classification Process. The first site in the series, former Camp Sibert, had only one target-of-interest and item “size” was an effective discriminant. A hillside range at the former Camp San Luis Obispo in California was selected for the second of these demonstrations because of the wider mix of munitions, including 60-mm, 81-mm, and 4.2-in mortars and 2.36-in rockets. Three additional munitions types were discovered during the course of the demonstration. The third site chosen was the former Camp Butner in North Carolina. This site is known to be contaminated with

items as small as 37-mm projectiles, adding yet another layer of complexity into the process. Additional sites including this one provide opportunities to demonstrate the capabilities and limitations of the classification process on a variety of site conditions. This site was selected for demonstration because it is more heavily wooded than prior demonstrations and is thought to contain a wide mixture of munitions. These two features increase the site's complexity and both characteristics are likely to be encountered on production sites. The tree cover poses a navigation challenge by increasing the difficulty of obtaining accurate global positioning system (GPS) readings.

## **4.2 SITE HISTORY**

In 1941, construction began on the 30,618 acre Spencer Artillery Range and documentation identifies establishment of two impact areas: Jakes Mountain (5,060 acres) and Bald Knob (2,090 acres). Troop training took place until September 1944, by which time Army ground forces had either departed or were under orders to depart. Subsequent arrangements were made for Dyersburg Army Air Field to use the Spencer Artillery Range as an air-to-ground gunnery range. The land reverted back to the original 25 leaseholders in the summer of 1946. Several surface decontamination sweeps were completed on portions of the former range in the 1950s. Since then, numerous tracts of land have been sold and/or subdivided, significantly increasing the number of property owners from the original 25 to several hundred landowners today.

## **4.3 MUNITIONS CONTAMINATION**

The suspected munitions at this site include:

- 37mm projectiles,
- 75mm projectiles,
- 76mm projectiles,
- 105mm projectiles, and
- 155mm projectiles.

Small Industry Standard Objects (ISO2) were added to increase the number of native munitions.

## **4.4 SITE CONFIGURATION**

The boundaries of the three sub-areas are shown in Figure 3. Note that the open field area had been recently cleared of trees, but that is not reflected in the aerial photo. Shape files delineating the demonstration site boundaries and the underlying grid system were made available from the ESTCP Program Office.

## 5.0 TEST DESIGN

The goal of the study is to demonstrate and characterize detection and discrimination with the MPV. Sensor classification performance is characterized as a function of the size and depth of the buried targets and the presence and effect of aggravating factors (nearby object, magnetic soil and complex terrain).

### 5.1 DEMONSTRATION SCHEDULE

The field survey was completed in two weeks. The daily report is included in Appendix E. The first day was set for preparing the survey: unpack, assemble the sensor, set up the survey, train crew and acquire calibration measurements on training pit and IVS. Because of the presence of another field crew the survey began in the forested area before proceeding to the dynamic detection area, which lasted just over 2 days. The dynamic survey data were analyzed by the PI while the crew moved to cued data. Most of the data pre-processing was performed during the deployment. Feature extraction and classification was done in the following months. The Gantt chart in Table 2 shows the schedule for each phase of testing and how the various phases are related.

**Table 2: Demonstration steps**

Tasks and demonstration timeline	Preparation Calibration			Field surveys			Post survey analysis		
	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
Mobilization – Demobilization	X					X			
CALIBRATION: Training pit		X							
CALIBRATION: Inversion and parameters stability analysis of training pit data		X							
CALIBRATION: Twice-daily test strip survey and data analysis			X	X	X				
DYNAMIC SURVEY: Detection in dynamic area				X					
DYNAMIC SURVEY: Target picking					X				
CUED SURVEY: Wooded area and dynamic area					X				
DATA PRE-PROCESSING: Cued data					X		X		
DATA ANALYSIS: feature extraction								X	
DATA ANALYSIS: classification ranked list								X	
RETROSPECTIVE ANALYSIS									X
REPORTING									X

### 5.2 SYSTEM SPECIFICATION

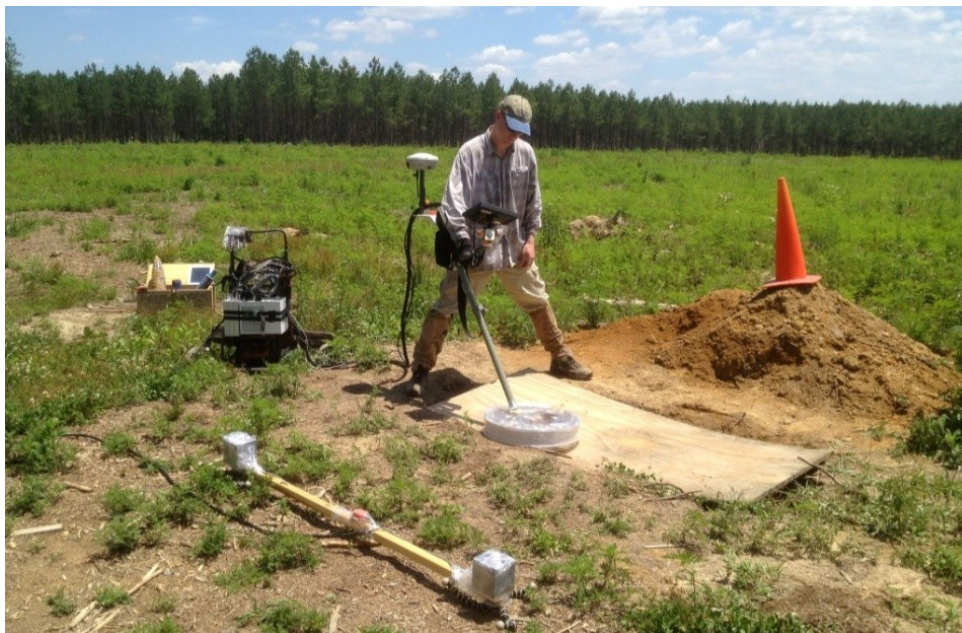
For cued interrogation mode the system is set for 25 milliseconds (ms) excitation and 25 ms recording of EMI transients. This is accomplished by using 0.9 seconds (s) data blocks that include 9 repeats (100 ms per cycle). Station time is set to 6.3 s by stacking 7 data blocks

(effectively  $9 \times 7 = 63$  cycles are averaged). Digital receivers use a 4 microsecond sampling rate. The data are recorded with 133 logarithm-spaced time gates (0.05% gate width) from 0-25 ms. Dynamic survey is set with 2.7 ms time window and short 0.1-s data block so as to reduce smearing of the signal by sensor motion.

The dynamic area has open sky and positioning is based on the GPS. In cued mode local positioning is achieved with the beacon system, though the GPS data are still recorded to verify beacon accuracy whenever enough satellites are visible, in particular at the IVS and in the open-field area. The GPS is a Trimble R8 that is mounted on the opposite end of the MPV handling boom. The GPS is also used to locate pre-programmed flag locations. A XSens MTi orientation sensor is mounted near the GPS to measure azimuth. The three-axis sensor data is also used for verifying the pitch and roll inferred from the beacon measurements. The beacon boom is laid on the ground within 2 meters of the survey flag. Boom orientation is recorded with a secondary XSens orientation sensor that is mounted at the boom center. Boom is generally oriented in the North-South direction on left side of target. After data processing, beacon-derived positions are located relative to the local flag and the geographic North, and subsequently globally-referenced using the supplied GPS coordinates of each flag.

### 5.3 CALIBRATION ACTIVITIES

Calibration is designed to verify correct sensor operation and calibrate the recorded sensor response over known targets. It was expected that 37mm, 75 mm and 105 mm projectile and small ISO could be encountered at the site. A target sample set was available for test pit measurements. Each item was successively placed inside a clutter-free training pit and surveyed in cued interrogation mode (Figure 4). A minimum of four different orientations and one depth per target were tested so that feature extraction and classification methods could be trained. Combinations with two objects were also tested.

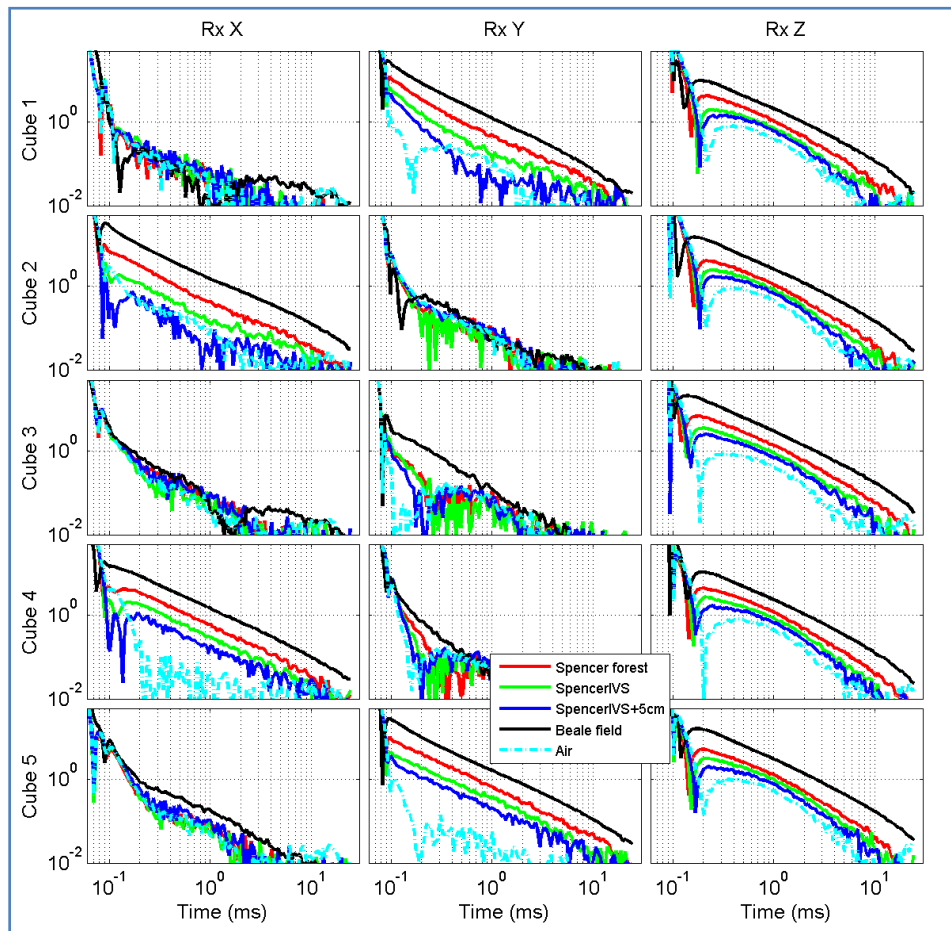


**Figure 4: Data collection over test pit. Reference TOI were placed in empty hole and surveyed in cued mode.**



The sensor was checked by surveying twice a day over an Instrument Verification Strip (IVS) where known targets are buried in a clutter-free environment. The strip was surveyed in dynamic and in cued modes so that detection and classification could be verified. Data were immediately inverted as an indirect means to verifying sensor reliability by examining stability of the recovered target parameters.

In-air measurements were regularly acquired, in particular before and after any battery change, to monitor variations in transmitter power and instrument noise. Background measurements were acquired with the sensor head on the ground for every tenth flag, after identifying a nearby “quiet” area that was diagnosed by examining the recorded decay curves in static mode. Data were subsequently analyzed to quantify the spatial and temporal variability in background noise and detect potential soil viscous magnetization. We found that the background signal was significantly weaker than that of the Camp Beale study (Figure 5).



**Figure 5: Background signal for static data at Spencer Range (field and IVS).**

The median value is shown for each of the 15 receivers (X,Y and Z components and cubes 1-5) and it is compared between the IVS, the forest and Camp Beale. One third of the cued interrogations were done with a ground clearance of 5 cm, using a foam pad riser; the corresponding background is shown for the IVS.

Beacon positioning was verified by comparing the locations that were predicted with the GPS/AHRS and beacon positioning systems wherever some of the GPS signal was usable.

## 5.4 DATA COLLECTION PROCEDURES

### 5.4.1 Sample density

Similar to previous demonstrations, cued interrogation soundings were collected around the marked target location (ground paint or flag). The first sounding was acquired at the marker. In general the operator followed a standard five-point square pattern as in Figure 6. At Camp Beale the pattern was conservatively augmented to 9 points but retrospective analysis showed that the additional soundings brought negligible benefit to classification. With five sounding and a cube separation of 0.2 m, a somewhat uniform spatial sampling is obtained with 0.6-0.7 m spacing between soundings locations.

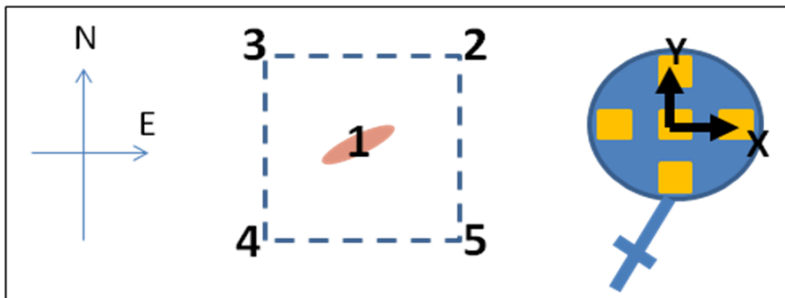


Figure 6: Cued survey pattern with five points centered on marked target location.

Detection survey was performed by walking along pre-defined survey lines (Figure 7) that were pre-programmed in the data acquisition software and physically laid on the ground. The sensor head was swept from side to side while keeping the sensor head parallel to the ground – the sensor track resembles a figure of “S”. Given a sensor footprint of 0.7 m, we started with a 1.5-m line spacing but found that the sweeping amplitude was too wide for our shortest field operator. Most of the survey was done at 1.2 m spacing. Station spacing depends on survey speed. Following an empiric rule such that the sensor should not move more than the receiver length (8 cm) during acquisition of a data block (0.1 s), sensor-head speed should be between 0.5-1 m/s with station spacing of 0.05-0.1 m along each of the 5 receiver-cube tracks. The resulting along-line speed is approximately 0.3 m/s.

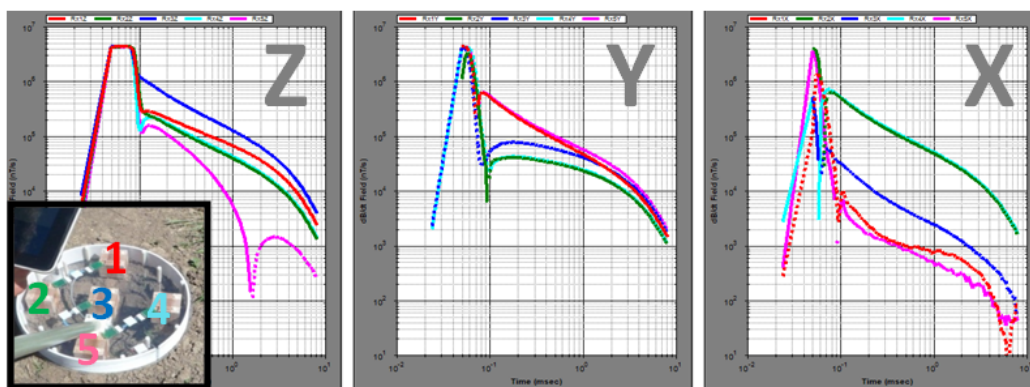


Figure 7: Picture of dynamic survey with MPV.

### 5.4.1 Quality checks

For detection survey the sensor track is displayed on the field monitor. The operator regularly checked the monitor for possible gaps. The second operator watched the main operator to verify the survey speed, sweeping amplitude and obvious gaps. For cued interrogation, each sounding is displayed immediately after acquisition to help the operator verify adequate anomaly sampling and data quality by examining data decay curves (Figure 8) and the arrows display. The first sounding requires particular attention to verify that the signal source originates right below the marked location. Offset can result from positional errors or difference in sensitivity between the detection sensor and the MPV and caused by an offset target or multiple targets. In such cases the operator is expected to apply close scrutiny to interpret all soundings, locate if possible signal source and acquire additional soundings if necessary. Anomaly coverage is verified by ensuring that the furthest receiver is measuring background. If residual signal from the target remains then additional soundings are collected to ensure full coverage of the anomaly spatial decay. For instance, if the MPV front receivers show above-background signal when the MPV is placed in position 2 (Figure 6), then a sounding is to be collected North of the middle of positions 2-3. If a nearby, interfering target is detected while being un-flagged for cued interrogation, then supplementary soundings are acquired to improve characterization of the two sources.

Data quality checks are first done during the survey to verify that receivers are properly operating. Any abnormal sounding is tagged and a new sounding is acquired at same location. In case of receiver failure survey is stopped until a solution is found - this never happened. Data quality is also controlled post-survey, while still on site, to identify possible issues and need for re-acquisition. Particular features to monitor are the spatial coverage of the anomalies, especially if the flag and anomaly peak are offset, beacon positions and signal to noise ratio.



**Figure 8: Typical target response when the MPV head is placed directly above a buried target. The Z-component data show that target is closest to center cube (#3) and equally distant from lateral cubes 2 and 4, while signal in cube 5 resembles background. The Y data confirm that target is buried between front and back cubes (1, 5) and X data confirm that target is located between side cubes 2 and 4.**

We ensure that all flags are visited by pre-programming their GPS coordinates and displaying their location on the sensor display map (Figure 2). Despite occasional GPS signal drops under the tree canopy, the GPS generally helps navigating between flags. Each visited flag is automatically marked on the map.



#### **5.4.2 Data handling**

Data are stored as .tem files on the DAQ and converted to .csv files before every battery change. We keep a copy of all .tem and .csv files on the DAQ, on a portable hard-disk drive and on the field laptops that is used for reviewing the data. The backpack bearing operator documents the survey by noting target names and file numbers in addition to any remarks made by the principal operator. Field notes are digitized every day by taking pictures of the notes and filling out a spreadsheet that is used for pre-processing.

## **6.0 DATA ANALYSIS PLAN**

### **6.1 PREPROCESSING**

The MPV computer DAQ records data streams from the sensor head, beacon receivers, attitude sensor and GPS with the GPS time stamp. The DAQ saves the data into a .tem binary file. Each sounding data is converted to a .csv file without any data alteration. Several pre-processing stages are performed before delivery to the analysts.

The beacon receiver data, transmitter current and attitude measurement are combined to infer the MPV head location. When the GPS Q factor is equal to 4 the GPS and attitude can be combined to predict the sensor head location and compare to the beacon. In case of discrepancy we consider the field notes, the relative distance to the beacon boom and any possible disrupting factors to choose the most likely solution or discard the sounding. At Camp Beale the beacon position was valid 100% of the time.

The MPV head EMI data is divided by the recorded transmitter current amplitude at turn off to normalize the response to a unit transmitter excitation, hence compensating for fluctuations in transmitter battery power. Background measurements are analyzed to define a background response to be subtracted from the cued data. A spatial parameterization of the background response can be utilized if significant spatial variability is observed. The resulting data is visually validated.

Because each sounding generates an individual data file, files must be combined to a single record for each target. The merged file is composed of data blocks for each sounding with the sensor location and attitude, sounding number and field comment. Only validated soundings are included. The final file name is comprised of the sensor and target names following ESTCP naming instructions. Files are later posted on a ftp site for distribution to analysts.

### **6.2 TARGET SELECTION FOR DETECTION**

Dynamic detection surveys are a novelty to this project. Dynamic data were collected at YPG and detection thresholds were identified. However, the site was clutter-free and only contained single targets at fixed locations. Therefore that data provided limited in-sight into live-site conditions and the target picking process was finalized on site based on prior simulations and comparison with local conditions and noise levels. Technical material on target detection are included in Appendix C and D.

### **6.3 PARAMETER ESTIMATION**

Advanced data analysis is done with UXOLab, a MatLab-based software jointly developed with the University of British Columbia and used in numerous ESTCP and SERDP projects. Data are inverted using a three-dipole instantaneous polarization model (Pasion and Oldenburg, 2001). The target polarizability decay parameters are the main features for the ensuing classification. Inversion setup parameters such as noise estimation are generally decided upon examination of the training pit data. Solutions with one or multiple targets are generated for every selected target. Decisions regarding the number of targets at a given location are made through statistical classification by prioritizing the most munitions-like solutions. Inversion results are reviewed by an experienced geophysicist to identify any potential issues with the inversion setup or with the data, and select data subsets as required for fitting all detected anomalies (masking).

## 6.4 TRAINING

Statistical classifiers were trained on a library of target features that had been accumulated during the previous surveys at YPG and Camp Beale, and adding new features associated with local targets. Measurements were collected over the training pit with local munitions. The items were placed in various positions and orientations so that parameter variance could be estimated.

After testing of the classifier, additional training data were requested to the ESTCP to obtain information about particular targets. Targets were chosen because they belonged to a cluster of unknown targets with similar features, or because some particular features stood out. Training data were iteratively requested until sufficient confidence in the classifier was attained. The classification decision memorandum detailed the training selection process (Appendix F).

## 6.5 CLASSIFICATION

The following guiding principles were applied:

- *Selection of features:* By analysis of the training data, those features that contribute to separation of the different classes (comprising UXO types and clutter) are selected. Our experience shows that the three sets of instant polarizability decays generally yield successful classification with the MPV (and other sensor data). The data are inverted in different manners, using single-target and multiple-target inversions and eventually different noise parameters or mask sizes. Therefore multiple sets of features can be extracted from the same anomaly and the model that most likely resemble a TOI is automatically selected through classification;
- *Choice of classification algorithm:* Methods are elaborated through analysis of the training data. Support Vector Machine (SVM) has been efficient at the past demonstration when applied through a cascading algorithm. Library misfit has also shown great success and has the benefit of being intuitively easier to comprehend;
- *Classification:* Anomaly labels are placed in a prioritized dig-list by using the classifier to compute probabilities of class membership for unlabeled feature vectors. The most likely TOI is reported in the dig sheet;
- *Number of UXO-classes:* When using a statistical classifier such as SVM, multiple UXO classes can be used to account for difference in sizes. For library misfit, each reference item forms its own class; there can be multiple instances of a given target type to account for its observed parameter variability, in particular for large objects for which orientation may affect the recovered polarizabilities.

We followed a similar method to that developed and successfully demonstrated in the past ESTCP demonstrations. Because the effect of magnetic soil was noticeably weaker than at Camp Beale, we were able to apply a standard classification methods based on library misfit. The method was detailed in the classification memorandum (included in Appendix F). The TOI library was initially based on items found at previous sites. The library was modified after training, removing items that did not seem to be present, and adding TOI which features differed from their typical reference class.

A multi-stage classifier was applied. The first stage included all polarizabilities (L123) and the next stages only used a combination of two polarizabilities (L12, L13), and the final stage only the main one (L1). Targets for which training data were available were also included in the classifier to assess the effect of classification parameters on their ranking. The decision to switch

from one classifier stage to the next was based on a decision statistic derived from the library misfit metric. For each stage, that metric shows a strong inflection when items strongly differ from library TOI (Figure 36 in Appendix F). The stage switch (or stop digging within this classifier stage) was automatically computed and further confirmed by visual inspection of the polarizabilities in ranked order (Figure 9) and comparison with ground truth data (obtained from training or earlier dig list stages).

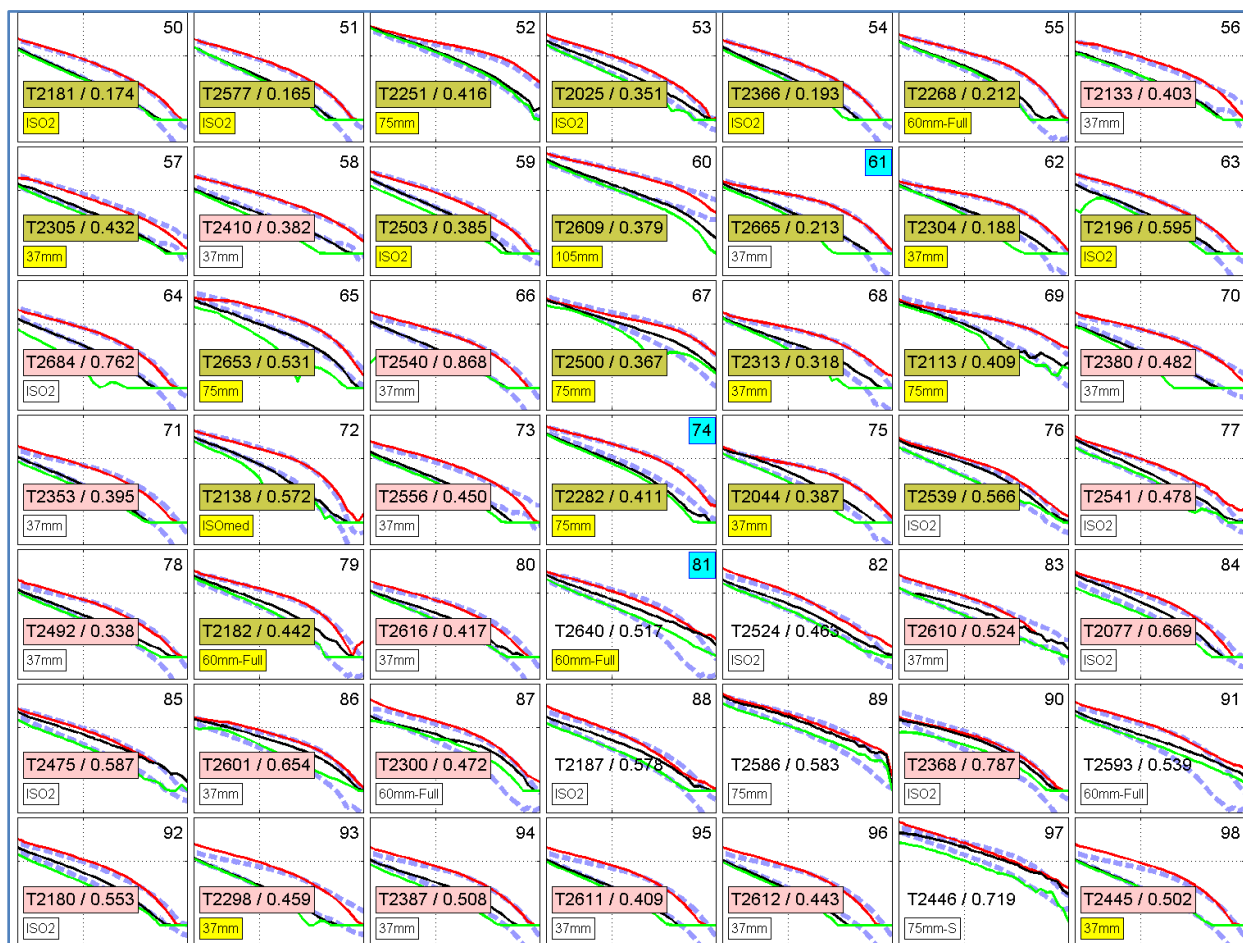


Figure 9: Polarizabilities for ranked dig list at classification stage 2.

In each frame the target polarizabilities are compared to their nearest library item, which caliber is indicated in a small text box. Target information is indicated with target identity and misfit in format Tnnnn/misfit. The text box is highlighted in yellow for a validated TOI and in pink for clutter. Blue boxes indicate stage switches in classifier.

The end product of classification is a ranked dig list that was formatted as in Figure 10. The first items on each list were those anomalies for which reliable parameters could not be extracted and therefore required excavation. Next followed the training items, then the “high confidence” munitions. Items were ranked according to decreasing confidence that the item was hazardous. Any items that were analyzed without reaching an unambiguous classification decision were placed next on the dig list. Finally, all items that were confidently classified as non-hazardous were ranked by their confidence.

[illegible]

*ESTCP MR-201158: MPV at Spencer Range*

## 7.0 PERFORMANCE ASSESSMENT

### 7.1 IVS repeatability

The IVS was surveyed in detection and cued interrogation mode. Data were inverted to indirectly assess repeatability. Inverted polarizabilities for the cued data are presented in Figure 11. The polarizabilities are almost perfectly equal, which confirms that the sensor was properly operating and that the operator was following a repeatable process that allowed for sufficient characterization of the buried targets.

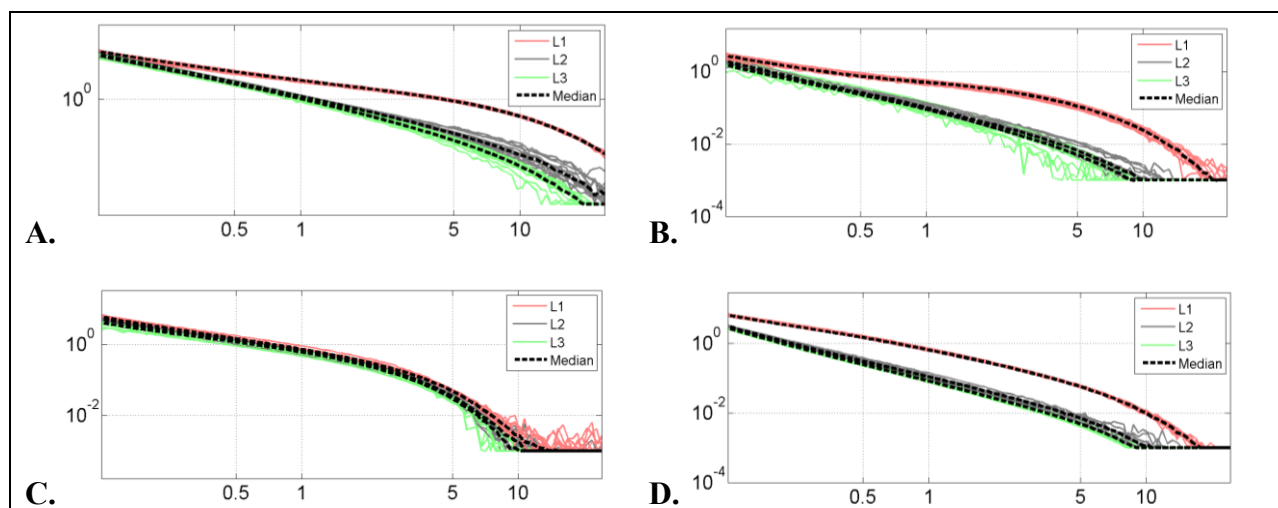


Figure 11: Polarizabilities on IVS lane: (A) 75 mm, (B) 37 mm, (C) Shotput and (D) ISO2.

### Dynamic data

The dynamic data were analyzed to verify detection of the IVS items. Data were also inverted to provide features for classification and assess stability. A detection map of 5 passes is presented in Figure 12, which confirms that all anomalies are detected with similar amplitude and footprint size on each pass. The first pass had some positional issues as the GPS update rate was too low, leaving large gaps between points - this is most visible on the second target from the top. This was addressed before starting the field survey.

The inverted polarizabilities are presented in Figure 13. Besides the first pass for which the predicted target tends to be too large because the peak anomaly is poorly sampled (panels B and D), we find that the recovered polarizabilities are relatively stable, although with a greater variability than cued data. The stability is sufficient to allow some classification with dynamic data, using higher tolerance for library matching.

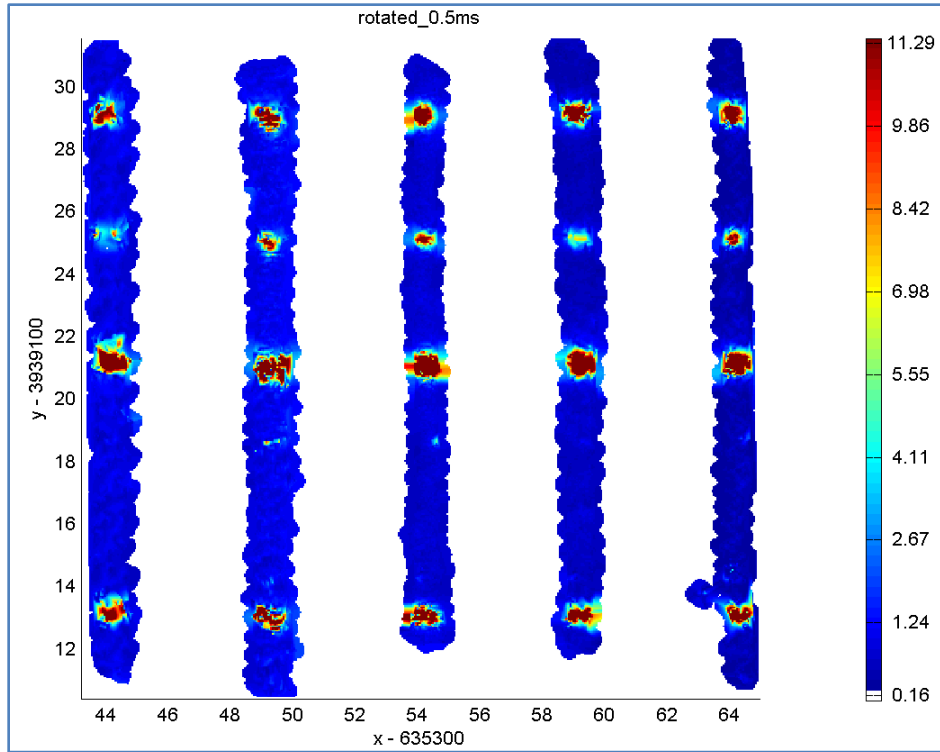


Figure 12: Map of multiple dynamic passes on the IVS.

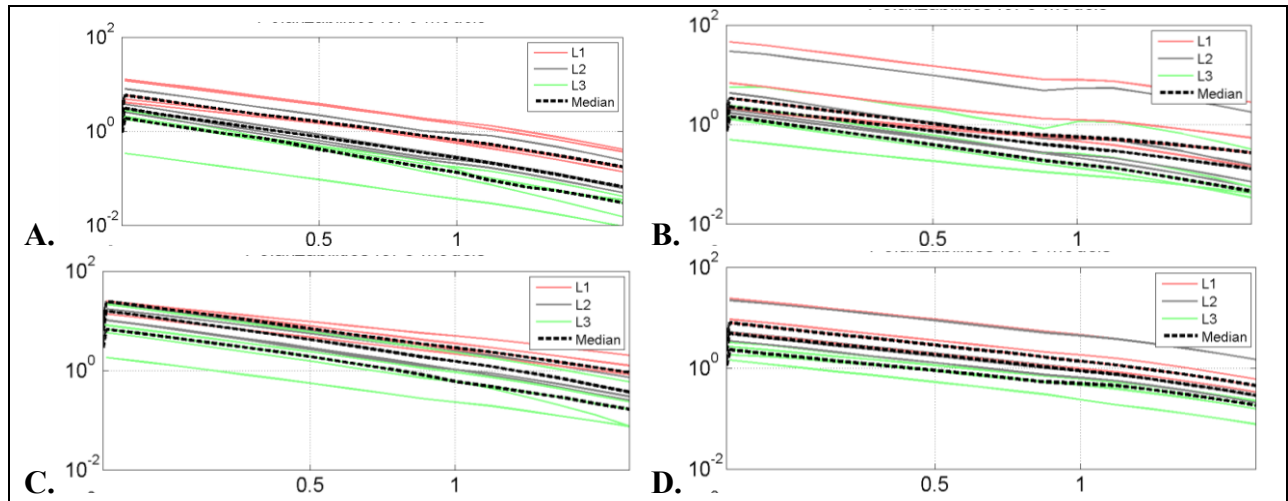
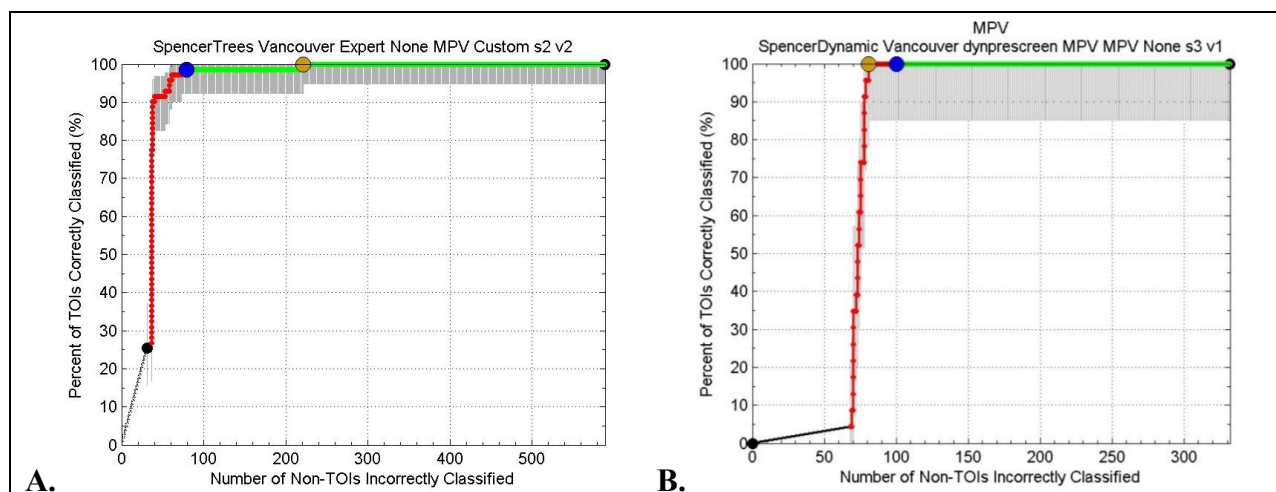


Figure 13: Polarizabilities of IVS items from dynamic data. (A) ISO2, (B) 37 mm, (C) 75 mm and (D) shotput.

## 7.2 Classification performance

Data analysis was split between the two survey areas: the forest where the three man-portable systems acquired approximately 700 flags in cued mode, and the open field dynamic area, when systems equipped with navigation and detection survey mode collected both dynamic and static data.



**Figure 14: ROC curves for the MPV surveys at Spencer Range.**

(A) Classification of cued data from treed area, one small ISO (#2355) was missed as part of a fragment pit;  
 (B) In dynamic area, dynamic data were used to classify some anomalies, like a prescreener, while ambiguous anomalies were analyzed using cued data.

Classification results are expressed in the form of a Receiver Operating Curve (ROC) in Figure 14. Classification was globally successful for the forested area and met the demonstration objective: 99% of the TOI were found after excavating only 15% of the clutter, half of which arising from training excavations. Moreover, the caliber of TOI was exactly predicted 92% of the time and differences in caliber were negligible 98% of the time (Table 3). Some 75 mm projectiles were occasionally confused with medium-sized ISO. Target SR-2640 was originally classified and reported as a 60 mm mortar although there were also strong model candidates for an ISO2 that would have naturally appeared 8 positions later in the dig list. This confirms that this flag was not placed in the dig list by chance. In general prediction of the target caliber was remarkably reliable at Spencer Range.

**Table 3: Targets with difference in caliber.**

Target ID	SR-2031	SR-2116	SR-2282	SR-2547	SR-2640	SR-2653
Validation	37 mm	ISO medium	ISO medium	ISO medium	ISO2 (small)	ISO medium
Prediction	ISO2	75 mm	75 mm	75 mm	60 mm	75 mm

### Missed target SR-2355

One TOI was missed in the forested area. Target SR-2355 is an ISO2 that was buried among four other metallic fragments. An illustration of the recovered target parameters that most resemble an ISO2 is shown in Figure 15. This result stem from a 2-source inversion. It was validated by a geophysicist after visual inspection. In retrospect and upon close scrutiny, there are signs that suggest potential issues with the results. Although the data are generally fit, some individual receivers are not well accounted for. This may be caused by the presence of more than 2 sources, or poor positioning, or some noise or malfunction. The recovered polarizabilities also



show different decay rates that could have been interpreted as a tell tale for the presence of a combination of targets. This suggests that inversion with more sources should have been attempted. In retrospect data were re-inverted with 3 sources but the recovered polarizabilities for the ISO2 were still too contaminated by a nearby object to allow clear classification.

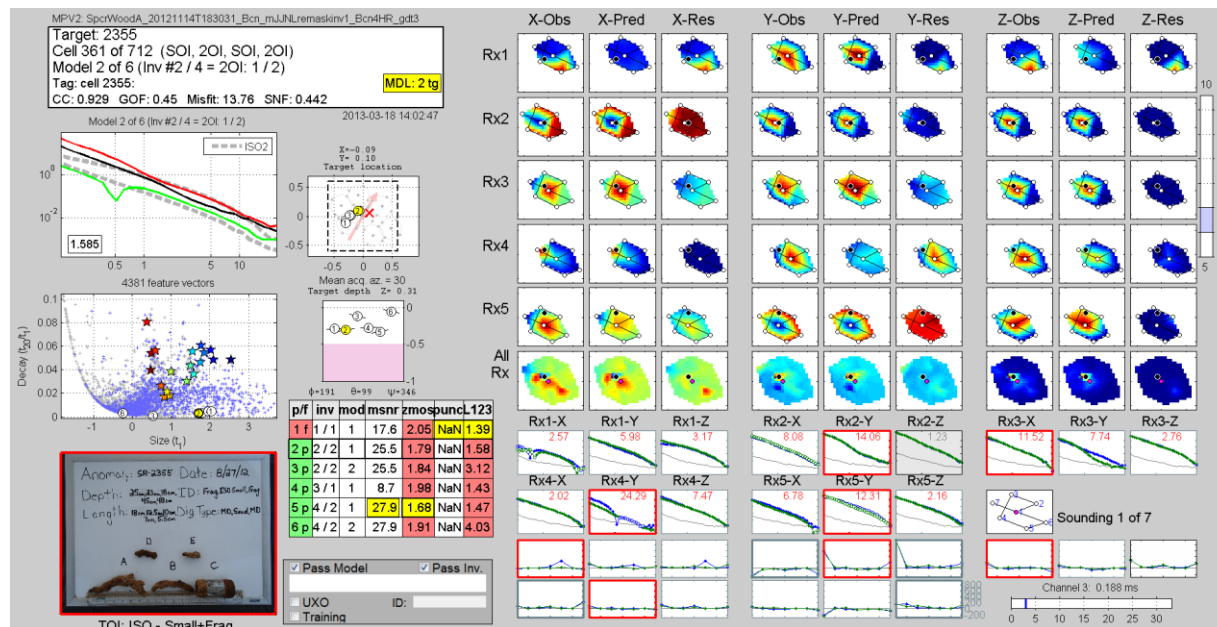


Figure 15: Target parameters for SR-2355, which was missed during classification.

The upper left graph shows in colored lines the recovered polarizabilities compared with the reference ISO2 in gray. A picture of the ground truth is in the lower left. Data fits for the different receiver components are shown as maps (columns Obs=observed, Pred=predicted, Res=residual for each of X, Y and Z components; rows for each of the cubes) and time decays on the right-side panels.

## Dynamic area

The dynamic area was processed under the principle that dynamic data could be used as a pre-screener, in which reliable data could be interpreted to directly classify some anomalies without need for a cued interrogation, whereas ambiguous anomalies would be further characterized using cued data. In this study we only processed data for the anomalies that we had selected from our survey data. We retained 288 anomalies, including 272 that were common with the EM-61 and the 2x2 TEMTADS within a margin of positional error. Some 70 anomalies were not included in our dig list because their signal was too low to be considered of interest. As a result we omitted these anomalies (these are indicated as "cannot analyze" and appear at the beginning of the ROC curve, which was designed to score a larger set of anomalies). Their associated dynamic data were subsequently inverted and analyzed and we confirmed that no TOI had been missed.

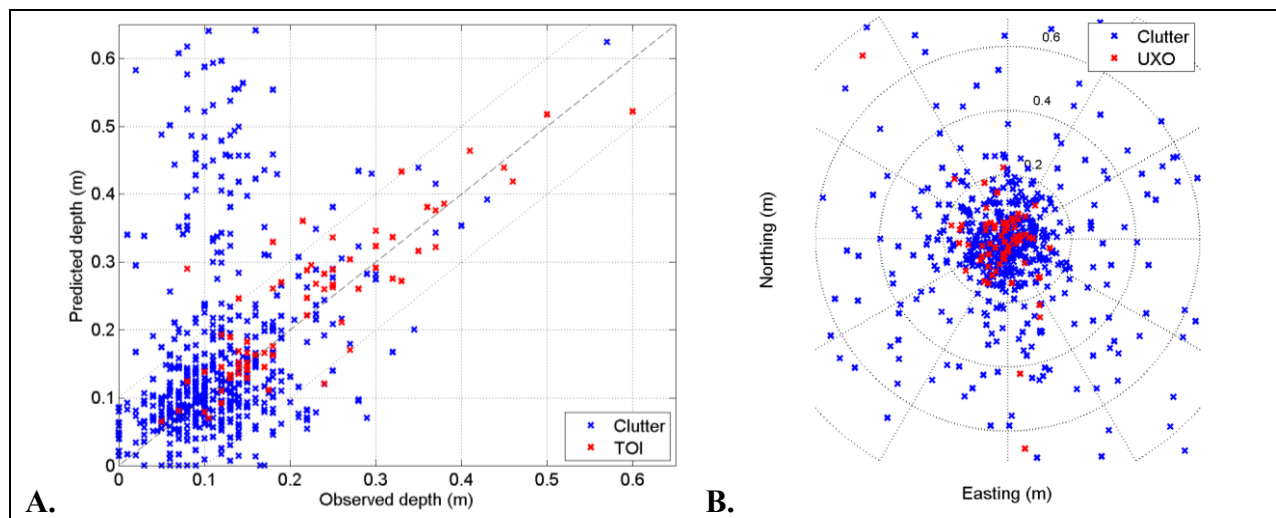
Dynamic data were extracted for the MPV 288 anomalies and inverted to attempt classification. Applying conservative metrics for data fit and spatial coverage, half of the anomalies were deemed to provide unreliable features for classification, while the other half was classified and generated the first stage of classification. The remaining anomalies were classified after inversion of their cued data. Classification was reliable and efficient with no-missed TOI and 90% clutter rejection.

Caliber was generally reliably predicted even with dynamic data. There were 4 instances where large differences in caliber occurred when based on dynamic data, though in every case the cued data provided the correct caliber: targets SR-1548 and SR-1626 were reported as 60 mm mortars instead of ISO2; target SR-1729 was reported as 75 mm projectile instead of 37 mm, although there were valid model candidates for the similar-sized ISO2 - the associated hole contained 5 pieces of metal, including one large piece, so that the aggregate could be confused with a large target. Similarly SR-1502 was reported as a 75 mm instead of a ISO2 with dynamic data because there were 3 pieces of metal, including one much larger than the ISO2 (correctly predicted with cued data).

In conclusion, the classification results confirm that high quality data can be collected with the MPV in dynamic and static mode, and that data processing methods are sufficiently mature to provide accurate, reliable and efficient classification in conditions of a site like Spencer Range.

### 7.3 Location and depth prediction

Successful classification relies on the capability to predict accurate target parameters, including location and depth. As expected from the previous section, we confirm that in general there was close agreement between the predicted target depth and location and the ground truth validation (Figure 16). There are some offsets for a few TOI; we believe that these are caused by disturbance in the GPS signal during the ground truth excavation; otherwise the MPV data could not have correctly predicted such distant targets. Offsets for clutter items can also be due to the presence of multiple pieces of fragments around a given flag.

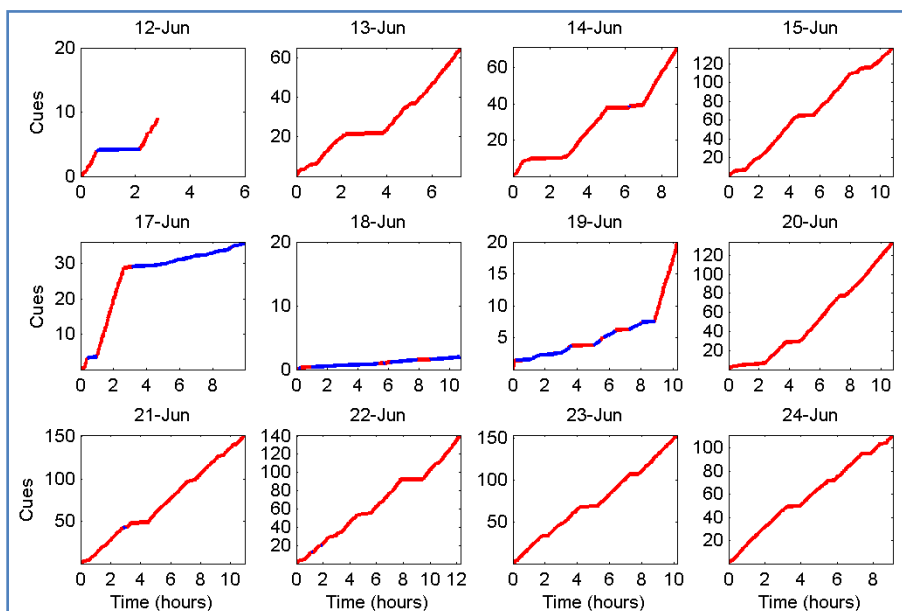


**Figure 16: Comparison of predicted location and depth with ground truth.**  
(A) Observed and predicted depth; (B) difference between observed and predicted location.

### 7.4 Field survey statistics and production rate

The demonstration took place over 12 days. A daily log is detailed in Appendix E. The first day was mostly spent on gathering the equipment, unpacking and testing the instruments off and on the IVS and test pit. Measurements of training items over the test pit took a total of 3.5 hours. The IVS was visited twice a day for 15 minutes per visit on average - 20 minutes when dynamic data were collected.

Cued interrogation covered 1006 flags, including only 24 reacquires due to large offsets between survey flag and detected anomaly or presence of secondary anomalies. Daily productivity is illustrated in Figure 17. On pure cued interrogations days the crew collected at least 120 flags, with two days at 150 flags over 10 hours. There were periods when up to 20 targets were collected in one hour; when counting the time for swapping of operator (every 1-2 h) and batteries (2-3 h) the average cued interrogation rate was 15 flags per hour.



**Figure 17: Graphical summary of daily data collection production rate.**

**Number of cued flags is shown as a function of time spent in the field each day: Cued interrogation (red), detection (blue) and interruptions (red plateaus: rain stopped operations on June 13, 14, 15 & 21 for several hours; 2 h visitors demonstration on June 19).**

The production rate was on par with expectations. The minimum requirement was to acquire at least 5 soundings per flag (applicable for 80% of the flags) and to regularly characterize the background noise, taking one measurement on the ground and in the air every seventh flag and before and after swapping batteries. On average, an anomaly was characterized with 6 soundings in the forest and 8 in the dynamic area, where the crew was instructed to track neighboring anomalies to account for differences in the picked locations between the MPV survey and the other sensors. One sounding typically took 15 seconds (7 seconds for acquisition, the rest for interpreting the data and moving the sensor head). In total 7200 static soundings were acquired for cued interrogation, 350 files for backgrounds, and 570 files for the IVS and test pit.

Dynamic collection was started on the fourth day, after another survey crew had cleared away from the area. The 1.3-acre survey area was covered in approximately 20 hours using two field operators most of the time. A third person occasionally helped laying survey lines to relieve the crew and minimize delay. Lines were interrupted after 30 m in order to save the file (total of 270 files), take a short rest and monitor the survey path on the display to control coverage. Some gaps between lines or near the edge of the survey were observed and therefore some partial lines were reacquired at the end of the survey (two hours), using the control display to locate the sensor head relative to previous survey paths.

## 8.0 COST ASSESSMENT

Time and resources were tracked for each task to assess the cost of deploying the technology at future live sites. The technology was still being improved at the time the demonstration took place. In particular, use of a new, dedicated AHRS on the beacon boom required modifications to the DAQ software (made by G&G Sciences) and to the beacon data processing algorithms, and led to additional studies. This demonstration was also the first time that detection data were collected and used for target picking, which resulted in on-site development work for the assimilation, characterization and interpretation of dynamic data. Sensor maintenance and data processing costs are therefore higher than expected for production-type surveys.

### 8.1 COST MODEL

A cost model for the Spencer Demonstration is proposed in Table 4. It is based on a burdened hourly rate of \$100 for any of the personnel involved. The field study was conducted with three people: one field technician, one field geophysicist with ample experience with the MPV technology, and one research geophysicist who managed the study, occasionally helped with data collection and handled all data processing tasks. Twelve days were spent on site.

**Table 4: Cost model for MPV demonstration at Spencer Range.**

Cost Element	Data to be Tracked	Estimated Unit Time	Estimated Total Hours	Estimated Total Cost
<b>Survey preparation</b>				
Sensor maintenance	Unit: \$ Cost • MPV maintenance and modifications			\$10,000
Pre-survey activities	Personnel: Geophysicist • Demonstration plan and coordination • Preparation of survey data		80 h	\$8,000
			40 h	\$4,000
Development time	Personnel required: Geophysicist		10 h	\$1,000
	Time to prepare assimilation of detection data		10 h	\$1,000
	Time to test target picking algorithms Time to integrate & test 2nd AHRS for beacon		40 h	\$4,000
<b>Field survey</b>				
Mobilization and demobilization	Cost to mobilize to site: 3 people	10 h	60 h	\$16,000
	• Flight, car, hotel, per diem	2 h	4 h	\$3,000
	• Shipping • Daily travel	2 h	72 h	\$7,500
Rentals, materials and miscellaneous	Survey equipment rental (GPS)		3 h	\$3,000
	Material supplies		20 h	\$1,000
	Miscellaneous tasks and interruptions			\$2,000
Instrument setup	Field crew: Geophysicist + technician			
	• First day: assemble, set up and test pit	8 h	16 h	\$1,600
	• Typical day (GPS set up and IVS surveys)	1 h	24 h	\$1,200
	• Analyze IVS data (Geophysicist)	0.5 h	6 h	\$600

Data collection for detection	Personnel : Field crew of 2 Personnel : Geophysicist Crew: Collect & record data per acre (total 1.3 acres)	4 h 15 h	6 h 40 h	\$4,600
Data collection for cued survey	Personnel : Field crew of 2 Personnel : Geophysicist Crew: Acquire, collect and record data per flag (total 1,000 flags)	3.6 min	15 h 120 h	\$13,500
Pre-processing and QC	Personnel required: Geophysicist Detection: Cost per acre Cued data: Cost per flag Cued data: Additional processing, post survey (study drift of beacon boom AHRS)	8 h 2.5 min	10 h 40 h 40 h	\$1,000 \$4,000 \$4,000
Data extraction	Personnel required: Geophysicist Time to built detection map per acre	10 h	13 h	\$1,300
Anomaly selection	Personnel required: Geophysicist Time to establish anomaly selection threshold and pick anomalies in dynamic data	8 h	11 h	\$1,100
<b>Data processing of detection data</b>				
Data extraction	Personnel required: Geophysicist Time to extract and mask dynamic data	2 min	10 h	\$1,00
Parameter extraction	Personnel required: Geophysicist Time for inversion & QC	3 min	15 h	\$1,500
Classifier training	Personnel required: Geophysicist Time to build feature library for dynamic data	2 min	10h	\$1,000
Classification and dig list generation	Personnel required: Geophysicist Time required	2 min	10 h	\$1,000
<b>Data processing of cued interrogation data</b>				
Data extraction	Personnel: Geophysicist Time to extract and mask cued data	1 min	17 h	\$1,700
Parameter extraction	Personnel: Geophysicist in training + expert Time for inversion & QC	3 min	65 h	\$6,500
Classifier training	Personnel: Geophysicist Time to identify features and potential TOI	1.5 min	25 h	\$2,500
Classification and dig list production	Personnel: Geophysicist Time to prepare memo, apply classifier and assimilate ground truth	1.5 min	30 h	\$3,000

## **8.2 COST DRIVERS**

The MPV was developed to provide a moderate cost, reliable, portable sensor with advanced discrimination capabilities that can operate at sites with challenging surveying conditions. As a portable system, deployment logistics and costs for transport and operation are relatively lower than those of towed arrays or other vehicular-based systems. The primary costs are incurred for labor and travel for the operators, and the primary cost driver becomes the duration of deployment, directly related to the acreage to be surveyed as well as the difficulty of the terrain (steep, rocky, very uneven, and wooded terrain can take somewhat longer to survey because it is more difficult to hike across these areas).

## **8.3 COST BENEFIT**

The primary driver for developing the MPV is to make discrimination feasible at a wide range of sites where field conditions prohibit the use of cart-based systems, and for small-scale deployment where a small area needs to be surveyed or where anomalies need to be resurveyed at a lower cost than a cart-based system.

## 9.0 IMPLEMENTATION ISSUES

The MPV is based on technology that is not expected to be affected by any particular regulation. The MPV has low impact on its environment owing to its handheld deployment mode, which leaves surface impact and requires minimal site preparation and vegetation clearance. Some DoD sites do regulate radio frequency, which could affect use of GPS. However, there is no reliance on GPS for cued interrogation through the beacon, while detection surveys can afford lower spatial accuracy requirements with cotton thread and spool.

The original implementation objectives were to prove that high quality data could be collected and support reliable classification, to verify that such performance could be achieved within a handheld form factor able to sustain field use, and to assess viable deployment modes. The technology was tested for detection and cued interrogation. The quality of the collected data was sufficient to detect all TOI and correctly classify 99% of the TOI, thus exceeding the demonstration objectives. The production rate for cued interrogation improved by more than 30% without compromising classification performance. Maneuverability and ruggedness were considered to be adequate by our team, though our newer field member had a smaller stature and found the detection survey sweep to be uncomfortable - the handle could be modified in the future. Our crew was able to survey for up to 10 hours a day by regularly swapping roles between operating the MPV and carrying the DAQ backpack. Commercial users have not yet tested the technology.

The MPV tested in this study is a second-generation prototype built by G&G Sciences. It is not commercially available and there currently exist only one government-owned unit, which maintenance has to be sourced to G&G. Basic components are commercially available – receiver cubes and National Instrument DAQ computer and receiver modules – while receiver filters, transmitter coils and switches and DAQ software (EM3DAcquire) are G&G custom builds. The MPV requires an attitude and heading sensor; there is no standard communication protocol and few models are currently supported, which can incur significant costs if alternative attitude sensors are to be integrated such that they are compatible with EM3DAcquire. Any GPS can be used as long as it is set to send a standardized data sequence (e.g., NEMA formats).

The MPV is relatively straightforward to operate in the field for general use. One crew member was new to UXO surveys and was quickly trained to collect data and interpret the recorded signals, in particular for locating the signal origin and detecting malfunctioning receivers. Advanced manipulation of the user interface for setting up and troubleshooting communication with peripherals, GPS and attitude sensor requires more familiarity with the system. Experience with setting up a GPS is useful for the detection survey.

Instructions on survey protocols, such as acquisition parameters and cued survey patterns, are contained in the YPG and Camp Beale reports. General guidance on EM3DAcquire can be found on the Geometrics website for the MetalMapper sensor, which uses similar underlying technology. At this point we would recommend that an experienced geophysicist be associated with any data collection to guide field operators and frequently verify data quality.

## 10.0 REFERENCES

- Barrowes, B.E., O'Neill K, George, D.C., Snyder, S., Shubitidze, F. and Fernandez, J. P., Man-Portable Vector Time Domain EMI Sensor and Discrimination Processing. SERDP 1443 FY07 Annual Report, 2007.
- Bell, T., Geo-location Requirements for UXO Discrimination. SERDP Geo-location Workshop, 2005.
- Billings, S., Pasion, L., Lhomme, N. and Oldenburg, D., Discrimination at Camp Sibert using Time-Domain EM. SERDP/ESTCP Partners in Environmental Technology Symposium, Wash., DC, Dec. 2007.
- Gasperikova, E., Smith, J. T., Morrison, H. F. and Becker, A., BUD results from the ESTCP Demonstration sites. SERDP/ESTCP Partners in Environmental Technology Symposium, Wash., DC, Dec. 2007
- Lhomme, N., Barrowes, B. E. and George, D. C., EMI sensor positioning using a beacon approach. Proceedings of SPIE Defense, Security+Sensing, Orlando, Florida, April 2011.
- Lhomme, N., Demonstration of MPV Sensor at Yuma Proving Ground, Arizona. Demonstration Report. ESTCP Project MR-201005, 2011b.
- Pasion, L. & Oldenburg, D., A Discrimination Algorithm for UXO Using Time Domain Electromagnetics. Journal of Engineering and Environmental Geophysics, 28, 91-102, 2001.
- San Filippo, B., Norton, S. and Won, I. J., Precision Local Positioning of an EMI Sensor Using the Transmitter as a Beacon, SERDP/ESTCP Partners Symposium, 2007.



## APPENDICES

### Appendix A: Health and Safety Plan (HASP)

Health and safety procedures were followed as indicated below, and also complied with the ESTCP guidance for this demonstration.

- **Applicable local, state, and federal health and safety laws and regulations**

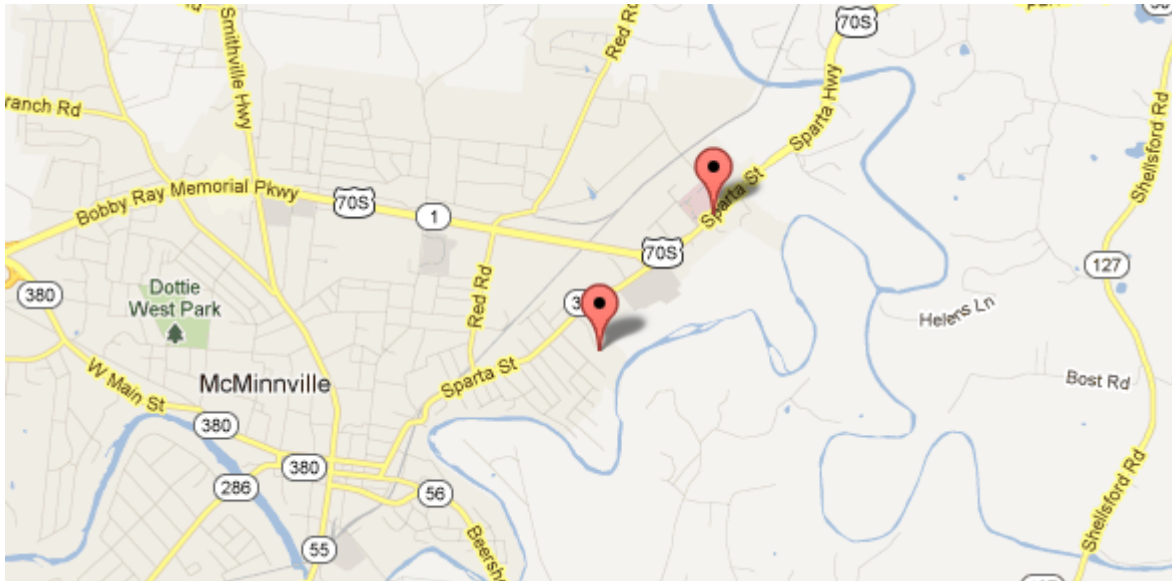
Field staff complied with health and safety requirements in accordance with Code of Federal Regulations (CFR), Part 29, Section 1910.120 and any site-specific requirements as noted during site orientation or other direction provided by ESTCP and Department of fish and Game representatives. Although 29 CFR 1910.120 pertains to personnel conducting activities at known or suspected hazardous waste sites and may not be directly applicable to the planned activities, the code provides a reasonable framework safe work practices.

- **Potential for worker exposure to hazardous materials and/or other hazards:** None or minimal. Any site-specific hazards also were to be briefed during orientation.
- **Physical requirements are expected of workers:** Basic fitness, heat resilience.
- **Number of people required to operate the technology:** Two field operators and one QC person (PI)
- **Technology's history of breakdowns or accidents:** No issues to date.
- **Potential effects from the transporting of equipment, samples, wastes, or other materials associated with the technology:** All components of the technology are inert, to the exception of Li-ion batteries that must be shipped by ground according to federal regulation.
- **Impact of technology on surrounding environment:** None. Technology is non destructive and man portable.
- **Closest medical facility:** There are two facilities near McMinnville, TN:

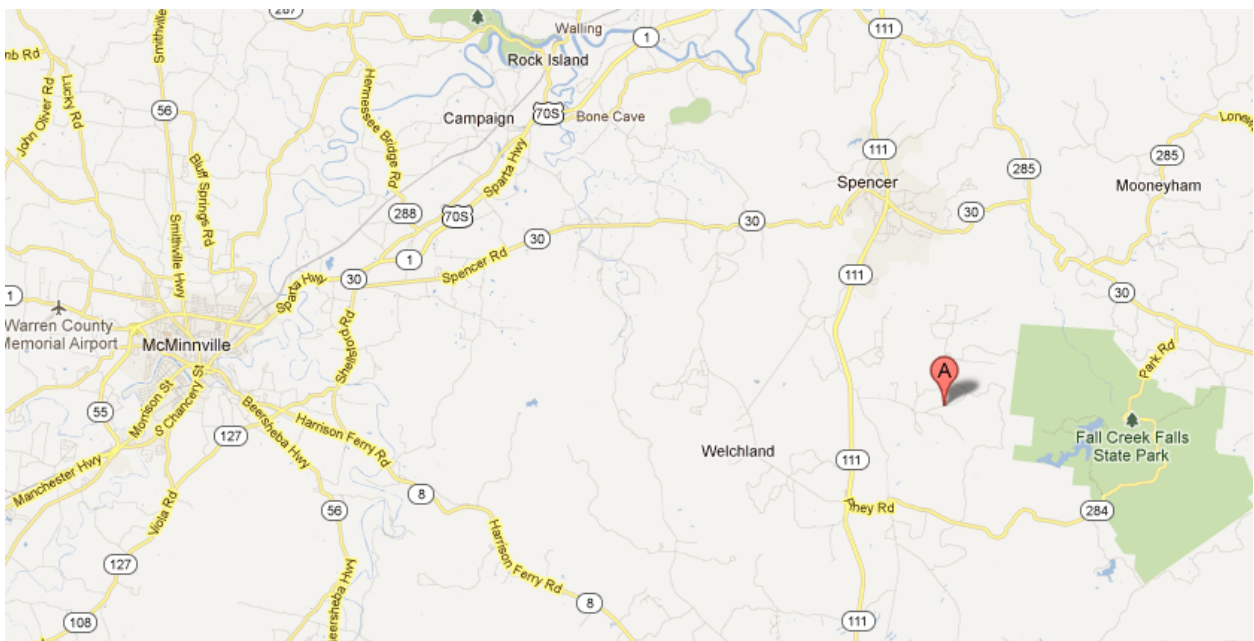
River Park Hospital: Located at 1559 Sparta Road, McMinnville, Tennessee, 37110. Telephone: (931) 815-4000

Middle Tennessee Surgical Care: Located at 145 Health Way, McMinnville, Tennessee, 37110. Telephone: (800) 364-5210 or (931) 507-6872

The facilities are indicated on the map of Figure 18 and Figure 19 relative to McMinnville and to the test area.



**Figure 18: Location of medical facilities: river Park in NE and Surgical Care in E.**



**Figure 19: Regional map with Spencer Range location relative to McMinnville.**

## Appendix B: Points of Contact

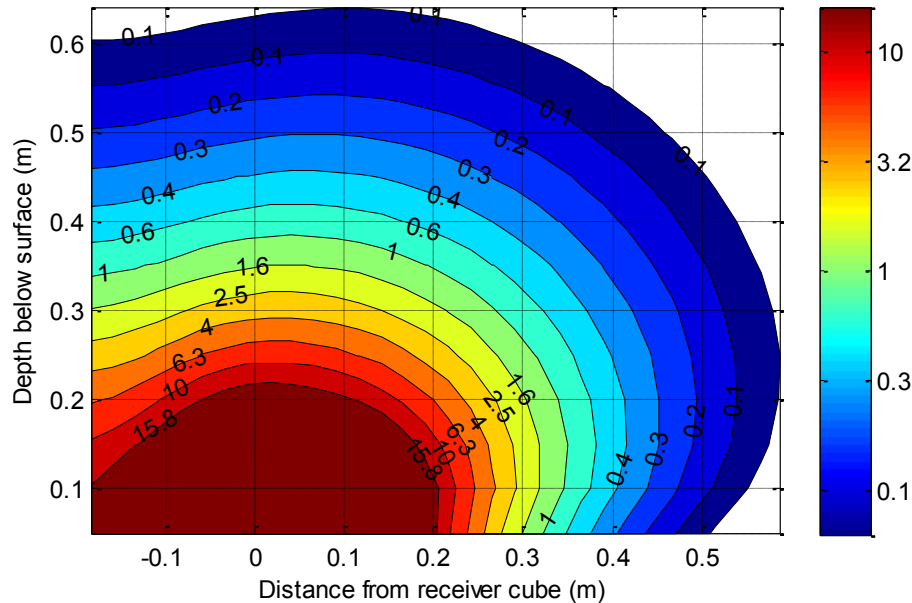
Points of contact (POCs) involved in the demonstration and their contact information are presented in Table 5.

**Table 5: Points of Contact for the MPV Demonstration.**

<b>POINT OF CONTACT Name</b>	<b>ORGANIZATION Name Address</b>	<b>Phone Fax E-mail</b>	<b>Role in Project</b>
Dr. Nicolas Lhomme	Black Tusk Geophysics, Inc. 112 A, 2386 East Mall, Vancouver, BC V6T 1Z3, Canada	Tel: 604-428-3382 <a href="mailto:Nicolas.lhomme@btgeophysics.com">Nicolas.lhomme@btgeophysics.com</a>	PI
David George	G&G Sciences, Inc. 873 23 Rd Grand Junction, CO 81505	Tel: (970) 263-9714 Fax: (970) 263-9714 <a href="mailto:dgeorge@ggsciences.com">dgeorge@ggsciences.com</a>	Sensor manufacturer
Dr. Herb Nelson	ESTCP Program Office ESTCP Office 901 North Stuart Street, Suite 303 Arlington, VA 22203-1821	Tel: 703-696-8726 <a href="mailto:Herbert.Nelson@osd.mil">Herbert.Nelson@osd.mil</a>	ESTCP Munitions Management Program Manager

## Appendix C: Detection range with MPV survey

We determine the spatial coverage requirement for an MPV survey by assessing the MPV footprint with a particular focus on the signal on its side receivers. We simulate 37 mm projectile at various horizontal offsets and depths in horizontal position (weakest signal) and vertical orientation (shortest spatial decay); the we compare with strong background signal (Beale soil). Polarizabilities are extracted from static data (proven to have similar decay as dynamic one in 0-2.7 ms excitation range) and background noise is taken from measurements Camp Beale, where their intensity was above normal.

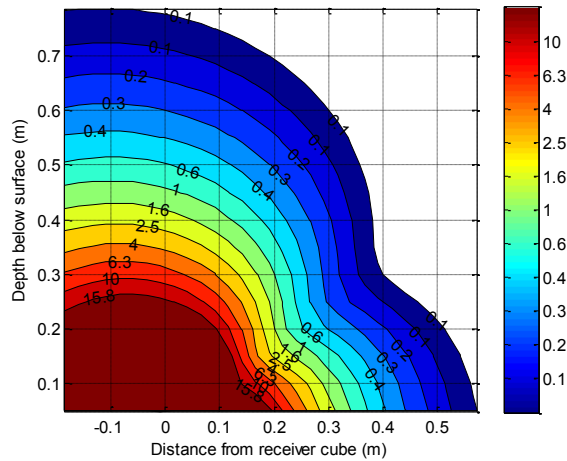


**Figure 20: SNR cross section for different target offset and depth relative to side receiver.**

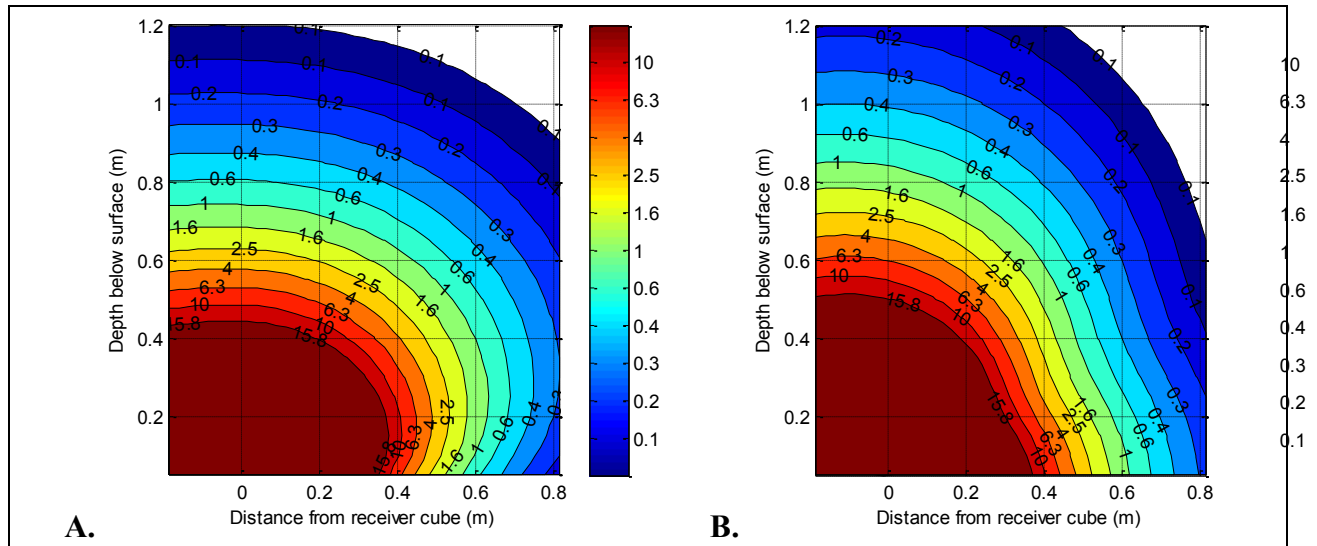
The target is a 37 mm projectile place in horizontal orientation. Noise is based on Camp Beale magnetic soil. Reference receiver is MPV side cube #2. Negative coordinates correspond to inner MPV. SNR=1 when signal and background have equal amplitude; target are detectable when SNR>1.6 (signal is 60% larger than noise).

The relative amplitude of target signal and background noise (Signal to Noise Ratio or SNR) is illustrated in Figure 20 for a typical 37 mm in horizontal orientation. The figure shows the SNR for different positions and depth of the target relative to a side receiver on the MPV. When the target is below the receiver (Distance=0), it is detectable at 35 cm depth as signal exceeds noise by 60% (SNR=1.6 contour). Similar detection signal would be observed with 10 cm lateral offset. At 20 cm offset detection would remain clear at 30 cm depth. If the target was vertical it would be clearly detected at 35 cm depth with a lateral offset of up to 15 cm (Figure 21). Therefore we can assume that a 10 cm target offset would not harm detection of a 37 mm target.

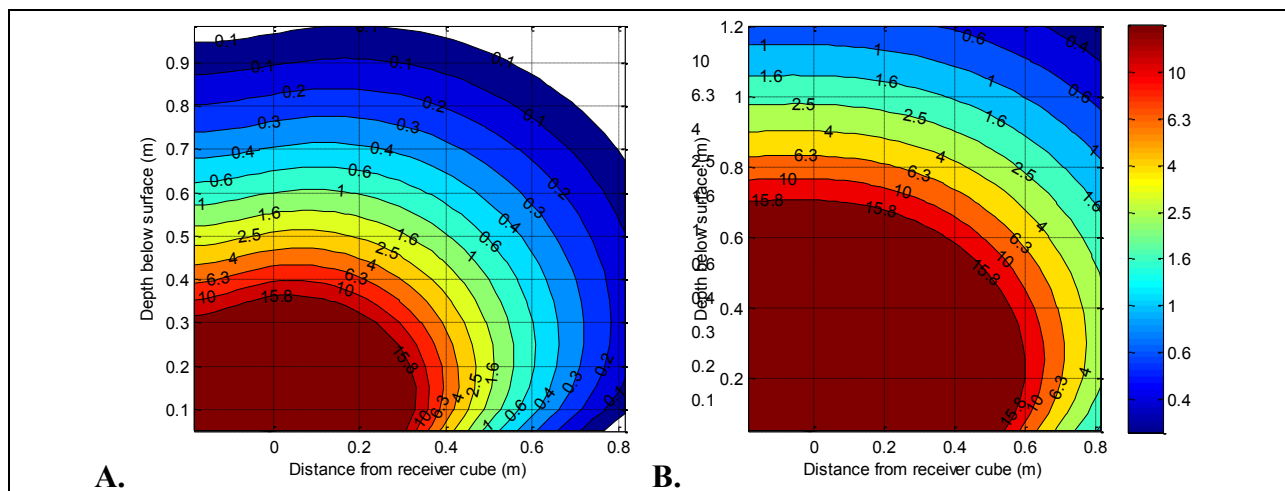
Simulations for a 105mm projectile suggest detection in Camp-Beale-type conditions at 70 cm with 10 cm offset (Figure 22). Detection depth would increase by 20-30 cm at a site with low background response (Figure 23). Overall detection depth is generally unaffected when the target is up to 10 cm away from the sensor head and therefore the sensor footprint is approximately 70 cm (50 cm diameter sensor head).



**Figure 21: 37 mm target in vertical orientation.**



**Figure 22: SNR cross section for 105 mm projectile; (A) Horizontal; (B) Vertical.**



**Figure 23: Survey in quiet background (Beale IVS) over 37 mm (A) and 105mm (B).**

## Appendix D: Root Cause Analysis for Missed Detection

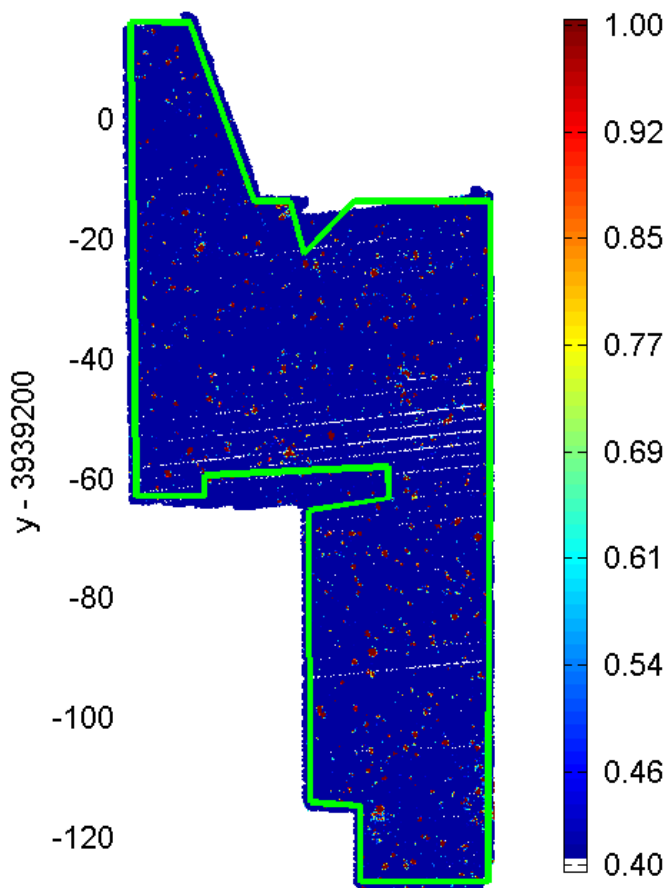
This document discusses the causes for missing three targets in the MPV detection list that was submitted during the Spencer Range survey. The following analysis shows that the targets were detectable and that the error came from the rushed interpretation stage.

### 1. Background

This demonstration was the first time that dynamic data was collected and used for target picking. Data analysis, mapping and target picking were performed during the Spencer Range deployment. Time was critical as the target picks had to be submitted to a third party for review, and then picks had to be surveyed in cued mode by the MPV field crew. Handling of dynamic data was initially slow, as each survey line was first examined to verify data quality and coverage, and then added to the other lines to build up a map. Unfortunately that initial detection map was built with incorrect spatial coordinates due to an error with the internal MPV software in converting the GPS longitude-latitude to UTM coordinates. This caused irresolvable spatial offsets that made the first submitted target list unusable and caused significant delay in validating the MPV detection picks relative to other sensor picks.

The raw GPS data were valid. The MPV and GPS data were re-imported to produce a new detection map, using our own conversion from longitude-latitude to UTM coordinates as part of our data import process. Because of the tight schedule, we tried to save time by loading only the data that lay within the survey boundaries – doing so would reduce the volume of data and bookkeeping of targets outside the survey boundaries.

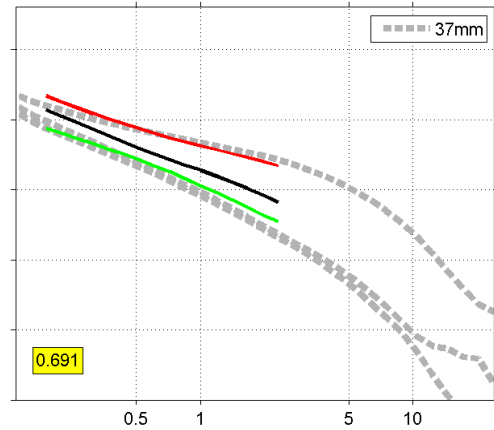
The following analysis shows that two of the missed targets were located within 0.15 m of the survey boundary; as a result, their corresponding anomalies were truncated and did not meet the detection criteria. The third anomaly was merged with its nearby anomaly and should have been picked with adequate quality control.



**Figure 24: Detection map of Spencer dynamic area; MPV total field data at 1.4 ms. The survey boundary is indicated with the green line.**

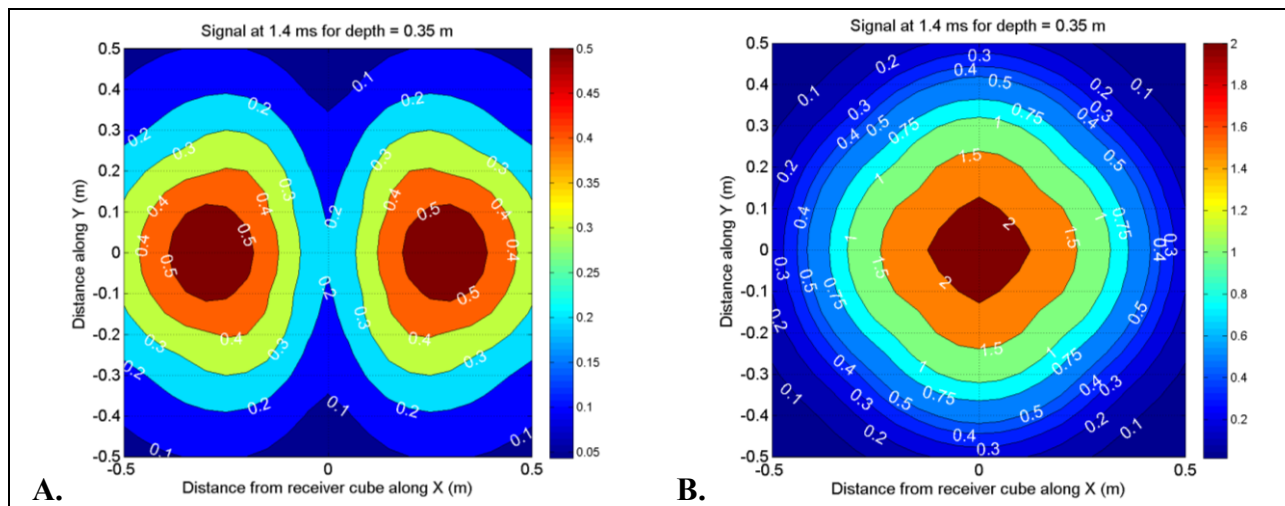
## 2. Target detection process

Dynamic survey data were assimilated, filtered and interpreted to identify anomalies that required further investigation. Anomaly selection was based on quantitative metrics derived from simulations and analysis of the worst case scenario for the expected targets. At Spencer Range the detection objective was to find 37 mm projectiles at 0.35 m depth. The typical response of that target type can be simulated to predict the anomaly amplitude and footprint. Model polarizabilities were extracted from static data; static polarizabilities have similar amplitude and decay rate as dynamic ones with 2.7 ms excitation, as shown in Figure 25 with static and dynamic data from the Spencer IVS.



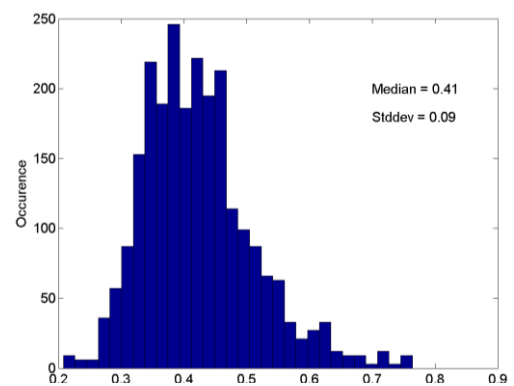
**Figure 25: Recovered polarizabilities for a 37 mm projectile based on inversion of static (grey lines) and dynamic (colors)**

The target response is shown in horizontal position (weakest signal) and vertical orientation (shortest spatial decay) in Figure 26.



**Figure 26: Predicted response for 37 mm projectile: horizontal (A); vertical (B).**

The ability to detect a target depends on its signal amplitude relative to the background noise variability. Noise in a detection survey originates from intrinsic sensor-electronics noise, environmental noise and sensor motion relative to the ground (if there is a soil response due to viscous remanent magnetization). The variability at the Spencer Range IVS is illustrated in Figure 27, where the total field data at 1.4 ms is shown over a target-free area (unleveled data). The background signal variability ( $1\sigma$ ) for the total field amplitude at 1.4 ms was 0.09 mV/A. After leveling, the data retains that variability and one could assume that a target would be



**Figure 27: Distribution of background**

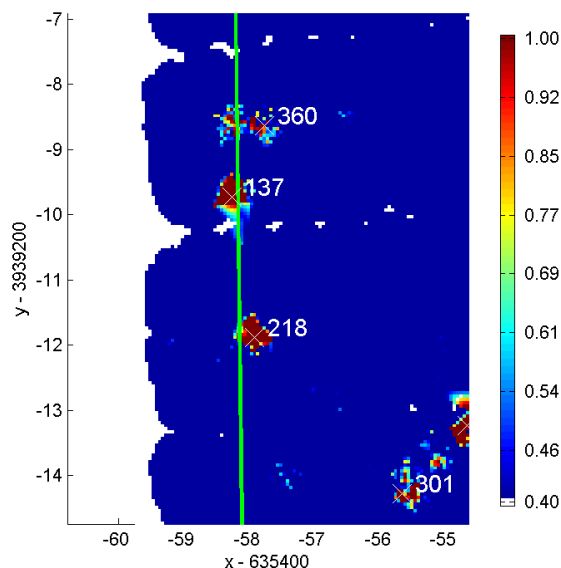


detectable when its anomaly consistently exceeded 2-3 standard deviations over a given surface area. Applying that automated method at Spencer, we obtained a list that we ranked according to the maximum amplitude of the 1.4 ms total field channel. Then we computed the ratio of the maximum amplitude for the 0.5 and 1.4 ms channels and eliminated the fastest decaying anomalies for the targets with the smallest amplitudes.

### 3. Missed targets

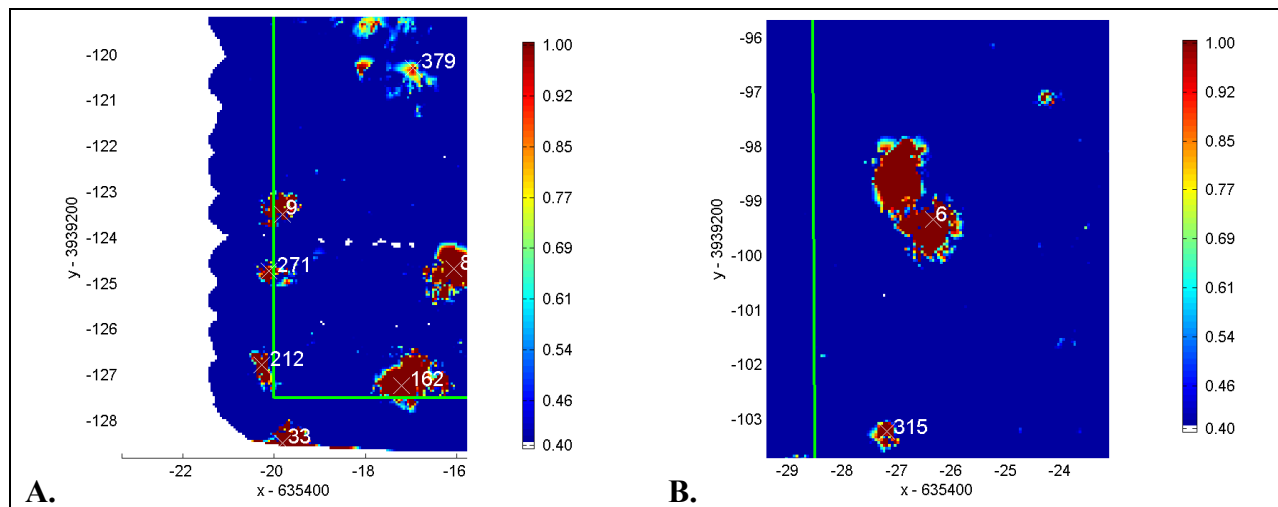
For the following analysis the data were re-imported with wider bounds. The target picking algorithm used the same thresholds, which were based on a minimum spatial extent at given signal amplitude. The 1.4 ms time channel was used under the assumption that small metallic scrap has fast temporal decay.

The first missed target was located at UTM coordinates (Easting = 635341.98 m, Northing = 3939191.38 m). The corresponding signal anomaly is shown in Figure 28 with label number 360 (ESTCP label SR-1766). The anomaly sits at the survey boundary. The target was missed by our analysis because the anomaly was truncated when importing only the data within the survey limits. As a result the anomaly extent was smaller than the minimal extent threshold.



**Figure 28: Detection map near the 1<sup>st</sup> missed target (360). The survey boundary is indicated with a green line.**

The second anomaly was located at UTM (635380.12 m, 3939075.22 m). Its corresponding anomaly is shown in Figure 29A, label 271 (SR-1506). The anomaly was missed for the same reason as the previous one. The target pick lies outside of the survey boundary.



**Figure 29: Detection map for the 2<sup>nd</sup> missed anomaly (A, marker #271 on the green survey boundary) and 3<sup>rd</sup> one (B, secondary anomaly 1 m to the North of marker #6).**



The third target was located at UTM(635373.05 m, 3939101.52 m). Its corresponding anomaly is shown in Figure 29B, where one large or two adjoined anomalies relate to label 6. The missed target location (SR-1555) is situated 1 m to the North of label 6 (SR-1554). The anomaly was missed because the two anomalies were grouped together because of a low amplitude threshold. Visual quality control would have picked the second target.

#### 4. Improving quality control

All three targets were missed because the process was rushed. The first two anomalies would have been picked if wider survey bounds would have been applied. For the third missed target, the original mistake was to use a small color range to enhance small-amplitude anomalies. Closer scrutiny shows that there are two targets and that they appear to be clearly separated when displaying the Z-component data (or the total field) with a wider color range and examining the transverse component data (Figure 30).

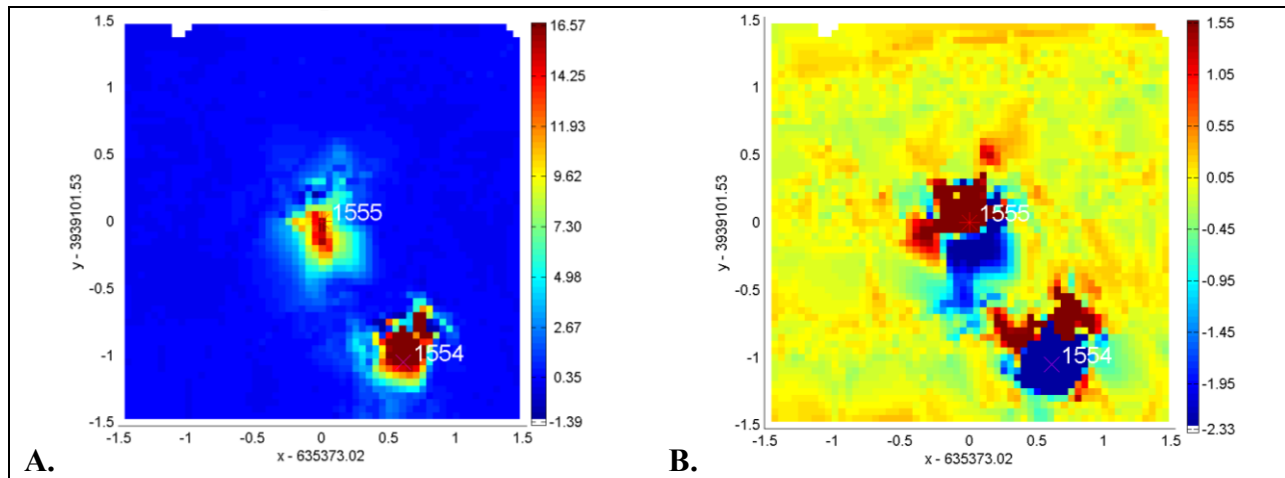


Figure 30: Re-examination of the 3<sup>rd</sup> missed target; Data for Z (A) and Y (B) component receivers.

#### 5. Conclusion

Moving forward, better detection of potential targets can be achieved by investing more effort in examining detection maps. Several maps could be utilized to include the information from different time channels and different components of the data. Comparison of multiple time channels can eliminate fast-decaying anomalies and separate large-amplitude anomalies like SR-1554/1555. Transverse component data help locate a target given that the X-component receiver data generally change from positive to negative amplitude near the target along the East-West direction, while Y data show the plus-minus switch in the North-South direction. Ideally this rich information content should be objectively assessed with quantitative metrics rooted in physics. Each anomaly above a given low-threshold value could be inverted with a point-dipole-type model to substantiate that analysis. This proposed method requires high spatial coverage and accurate positioning to limit distortion of anomaly extent. These conditions cannot always be met. Alternatively, every anomaly above a given amplitude threshold, irrespective of spatial extent, can be selected as a potential target. In this case there is no prescreening of near-surface metallic clutter and classification is only applied to cued interrogation data.

## Appendix E: Field notes

Monday, June 11: Travel (N. Lhomme + J. Jacobson) and prepare target list for cued interrogation (conversion and formatting). Fly, get rental car and pick up all survey equipment (everything fits in one Suburban car)

Tuesday, June 12: Bring all survey equipment to site (after delay with shipment). Assemble equipment and verify operation (2 hours), setup survey points for GPS navigation. Cued interrogation survey at IVS (20 min) and at training pit (2 hours).

Wednesday, June 13: IVS (20 min), training pit (1h) and start of survey in woods (area A, East of access road). Several rain interruptions. 50 targets

Thursday, June 14: J. Gayer joins survey team and gets trained at operating the MPV: theory, motivation behind SOP, interpretation of data on control screen to adjust survey pattern, programming of survey parameters, control of proper operation. Start survey at IVS and in woods with 3, then 2 persons. Lhomme starts daily QC cued interrogations: import data, verify beacon positioning accuracy, import in UXOLab and invert data, verify adequate spatial coverage of anomalies for stable target parameter recovery. Several rain interruptions. 70 targets

Friday, June 15: Cued interrogation by Jacobson-Gayer. Lhomme prepares detection survey (program lines) and QC cued interrogations. Thunderstorms and rain.

Sunday, June 17: Finish wood area A (2h) and start dynamic survey with 3 people. All train at dynamic collection on IVS (for every day of dynamic detection). Lhomme lays out 1.5-m-spaced lines and visually checks that survey speed and spatial coverage is adequate. 30% of area is covered (5-6h). Lhomme starts importing dynamic data and mapping to verify adequate spatial coverage.

Monday, June 18: Dynamic survey of middle area with 2 field operators and 3 person lying lines. Reduce spacing to approximately 1-1.2 m to make walking and sweeping sensor easier. Lhomme imports and maps dynamic data

Tuesday, June 19: Dynamic collection of southerner portion. Recollection of lines with wide line spacing and short lines. Demonstration of detection, cued interrogation and data processing to USACE visitors. End of dynamic detection and move to cued survey in woods. Lhomme prepares detection maps.

Wednesday, June 20: Cued interrogation in woods (140 targets). Lhomme prepares detection maps and submits target detection list based on simulated response of 37-mm projectile buried at 34-cm depth.

Thursday, June 21: Cued interrogation in woods (150 targets). Lhomme re-imports all detection data due to problematic geographical coordinate conversion in EM3D, re-applies detection algorithm and submits corrected detection list.

Friday, June 22: Cued interrogation ends in woods (88 targets) and starts in open field. Lhomme prepares cued interrogation list based on main list supplied by Amy Walker (272 targets detected by EM-61, TEMENTADS 2x2 and MPV) and 16 additional targets of interest for the MPV.

Saturday, June 23: Cued interrogation in open field (153 targets). Lhomme QC cued data

Sunday, June 24: End of main cued interrogations (82 targets). Lhomme QC data and requests 16 recollects in woods (targets detected near flag, over 0.5 m away) and 8 in open field (extend pattern for ambiguity on peaks of interest). Demobilize, pack and ship equipment.

Monday, June 25: Travel back home and report.

## Appendix F: Classification Decision Memorandum

Classification is performed using the standard UXOLab software. The cued data were inverted using standard inversion parameters as proposed in the demonstration plan. Results were reviewed to verify that the recovered models fit the observed data. When necessary, inversions were redone after altering model-search bounds or masking out some data in order to improve the fits. Models that did not fit the data of interest were rejected while all other plausible models were kept for classification. A spatial representation of the recovered models is shown in Figure 31, for which size and decay parameters were derived from inverted polarizabilities.

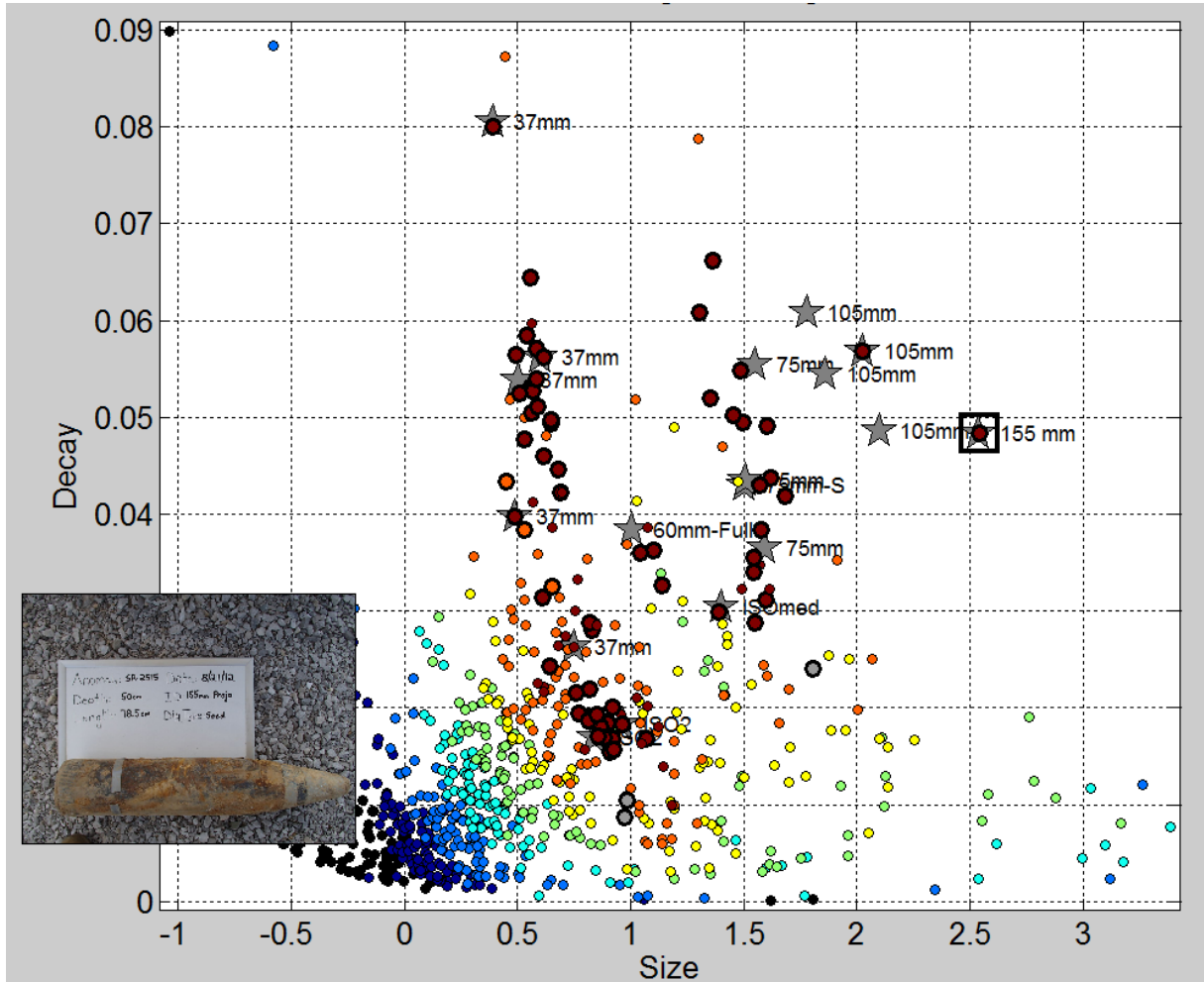


Figure 31: Distribution of target size and decay parameters relative to reference UXOs. Symbol colors reflect the likelihood that anomalies are potential UXO (based on library misfit).

### 1. Unclassifiable anomalies

Every field anomaly was adequately fitted with a model that either described a metallic object or a background response from the soil (which has moderate magnetic viscous remanence). However, some anomalies appeared to be on the edge of the cued survey and yielded target parameters that loosely resembled UXO. These anomalies were failed because recovered parameters could not be fully trusted to dismiss these targets as potential UXO.

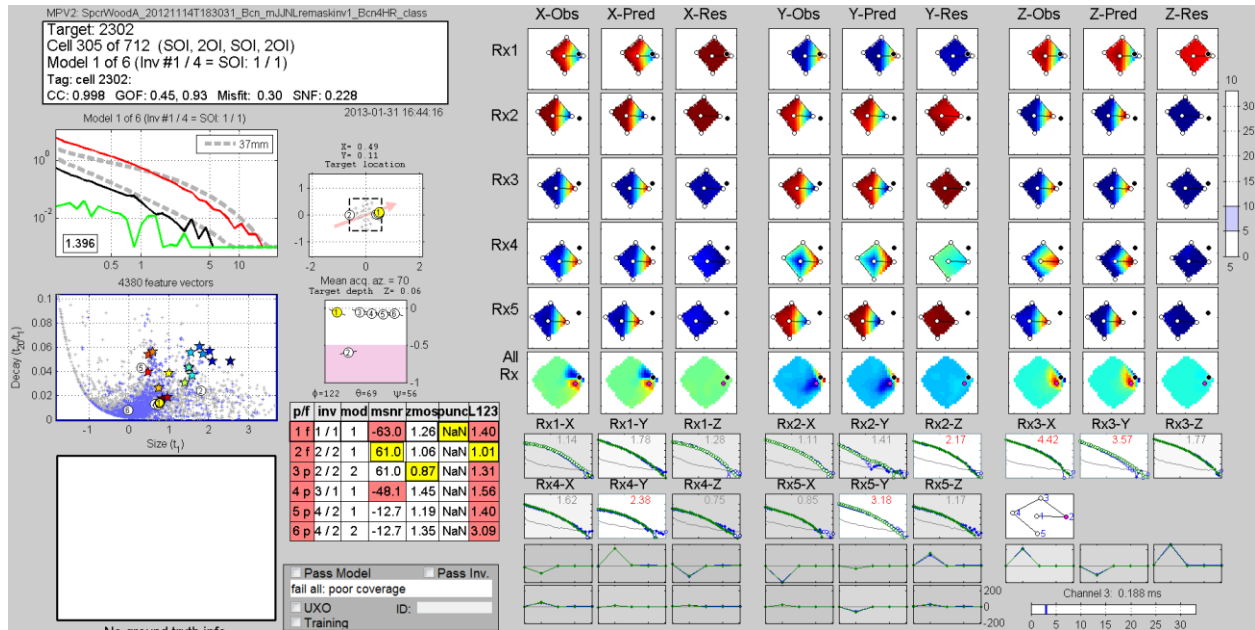


Figure 32: Failed anomaly on edge of survey.

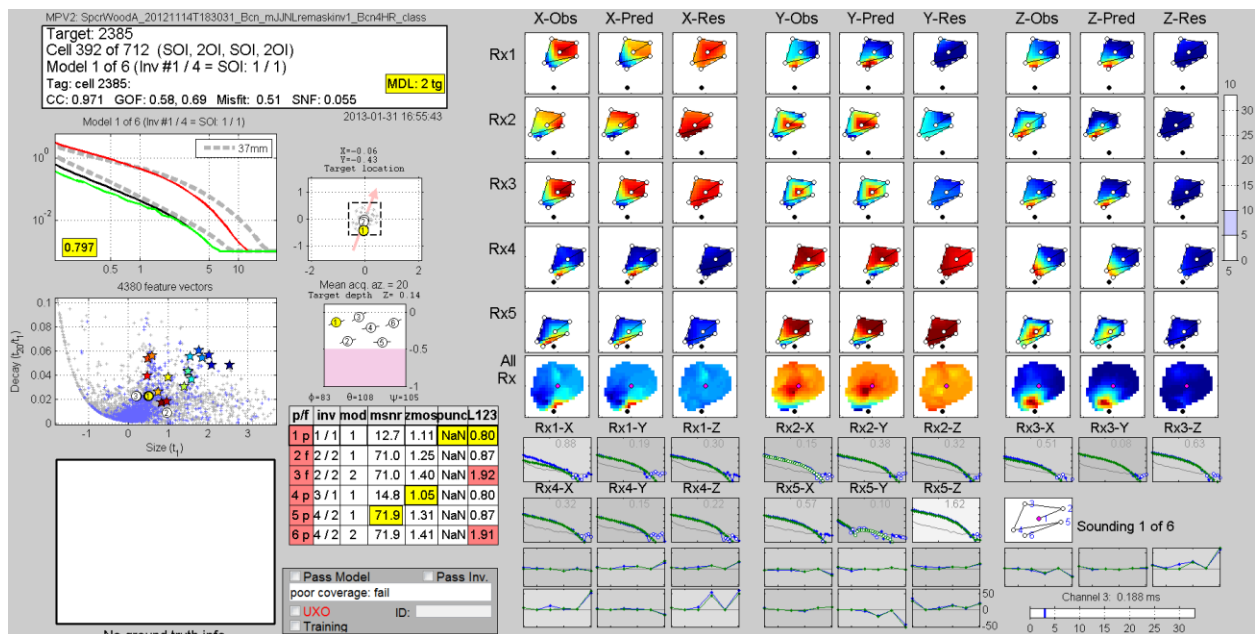


Figure 33: Failed anomaly on edge of survey.

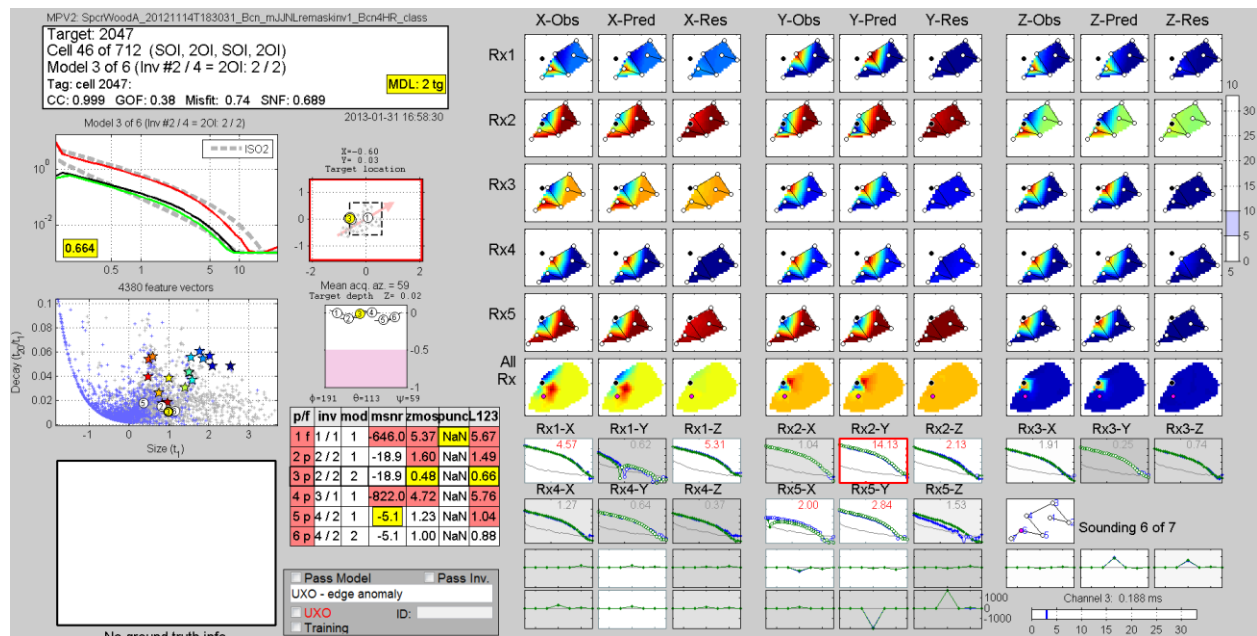


Figure 34: Failed anomaly on edge of survey.

## 2. Classification approach and features

Classification is based the recognition of typical UXO features. Potential UXO are identified because their recovered target parameters – or signature – resemble known UXO, or there are multiple occurrences of metallic objects with highly similar features. The classification features are the three time-varying, orthogonal polarizabilities that are derived from the geophysical inversion of field data.

## 3. Training data selection

A first set of anomalies was selected for training through cluster analysis of similar model signatures. Potential targets of interest included several circular, elongated metallic objects of similar or smaller size than the ISO that was used at Camp Beale, as well as fuze-like objects and larger targets up to a 155 mm projectile (Figure 35). The second pass was based on training items that were selected by the geophysicist who performed the inversion QC. These items were selected because they resembled known targets such as full and partial 60 mm mortars. After this training we resolved an earlier confusion between the “ISO2” and the medium ISO, which both seem to differ from the ISO encountered at Beale. The third round of training was requested to clarify that there was no Beale ISO, that there were indeed 60 mm mortars, and to confirm that multi-target such as 37 mm plus frag could be predicted. The training data summary table is shown below.

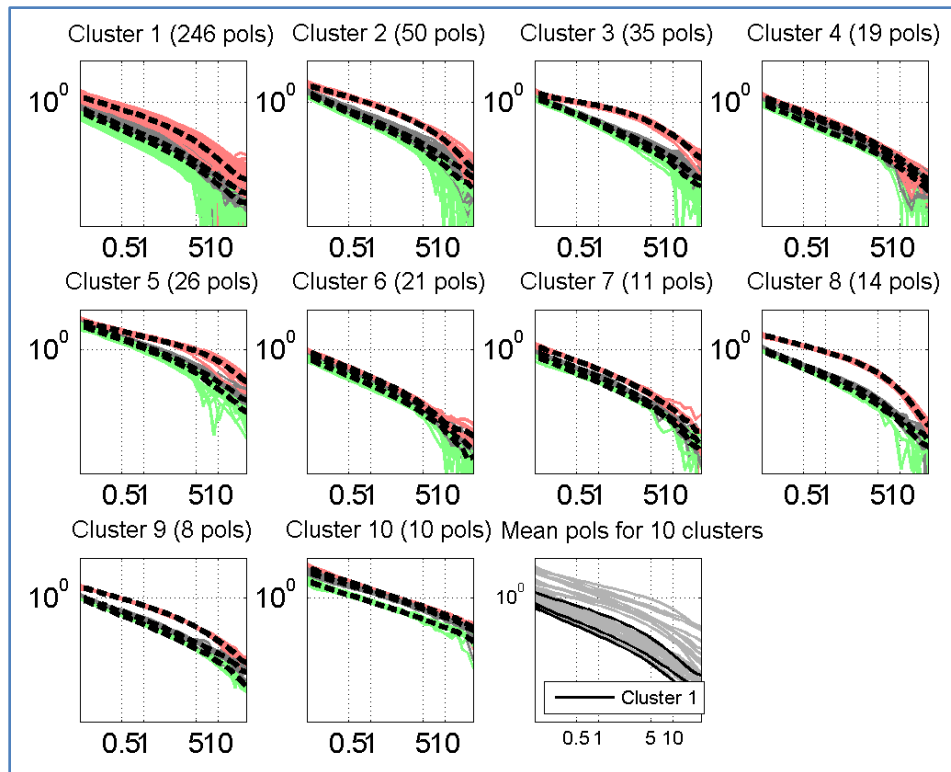


Figure 35: Cluster analysis of model parameters.

Table 6: Training data summary.

Target ID	Request	Similar to	Validated	Reason for selection
SR-2003	1	fuze	frag	
SR-2242	1	fuze	frag	
SR-2449	1	fuze	frag	
SR-2082	1	very small ISO	frag, frag	
SR-2108	1	small ISO	frag	
SR-2124	1	small ISO	frag	
SR-2208	1	small ISO	frag	
SR-2079	1	ISO (smaller L23)	frag	
SR-2231	1	ISO slower decay	frag, frag	predicted 2 tg
SR-2232	1	ISO very slow decay	frag, frag, frag	loglin decay
SR-2076	1	ISO2	frag	ISO2 shared with #2069?
SR-2099	1	ISO2?	frag, frag, frag	not perfect fit = sign of 3 frags
SR-2598	1	ISO2	frag	
SR-2616	1	ISO2	frag	
SR-2492	1	37 or ISO2	frag	different models GPS/beacon
SR-2262	1	75mm	75mm+frag	slightly faster decay
SR-2547	1	75mm	ISOmed	



SR-2402	1	big deep	frag shallow	soil + frag
SR-2601	1	37 or 81	frag	
SR-2653	1	75 or 81	ISOmed	Pb with early time saturation and depth
SR-2515	1	155mm	155mm	
SR-2519	2	ISO	frag	no ISO? Get more to confirm
SR-2091	2	ISO/ISO2	frag x 5	
SR-2133	2	ISO2	frag	gdt half way b/w 2133-2143
SR-2165	2	ISO2	frag, =2166	
SR-2084	2	ISO2/60mm	ISO2	
SR-2088	2	ISO2/60mm	ISO2	
SR-2361	2	37mm	37mm	
SR-2682	2	37mm	37mm	deep
SR-2137	2	60/75	frag	
SR-2077	2	60mm body	frag	
SR-2289	2	60mm full?	frag	slower decay and wider L12 separation
SR-2625	2	60mm/ISO2	ISO2+frag	
SR-2677	2	60mm full?	frag, =2684	faster decay and wider L12 sep
SR-2413	2	105mm?	105mm	
SR-2613	3	ISO	frag	offset
SR-2206	3	ISO	frag x 3	double with 2213
SR-2709	3	ISO	frag (=2704)	most lookalike+poor coverage
SR-2196	3	ISO2	ISO2	saturation?
SR-2541	3	ISO2	frag x 5	offset
SR-2610	3	37 or ISO2?	frag	offset
SR-2022	3	37+stuff?	37mm+frag	
SR-2410	3	37mm	frag (=2408)	double with 2408, wide L12 sep though
SR-2526	3	37mm	37mm+frag	saturation
SR-2139	3	37mm	37mm	smaller L1 or faster decay
SR-2678	3	37mm	37mm+frag	faster decay
SR-2182	3	60mm full?	60mm	L1L3 perfect, L2 in b/w
SR-2500	3	75mm	75mm	saturation
SR-2113	3	75mm	75mm	offset and deep

#### 4. Parameters and thresholds

We apply a multi-stage classifier using the same standard methods as those applied to other sensor data as part of ESTCP MR-201159. The classifier is primarily based on polarizability library misfits. The first stage uses all three polarizabilities (L1L2L3), the second L1L2, the third L1L3 and the fourth one just L1. Transitions from one stage to the next are selected by applying the classifier to the entire dataset and using the fact that some items were marked as UXO either during the inversion QC or from training data. For each stage the decision statistic resembles an L-shaped curve in which the elbow marks a transition in the statistic – stage thresholds are chosen near the elbow (Figure 36).

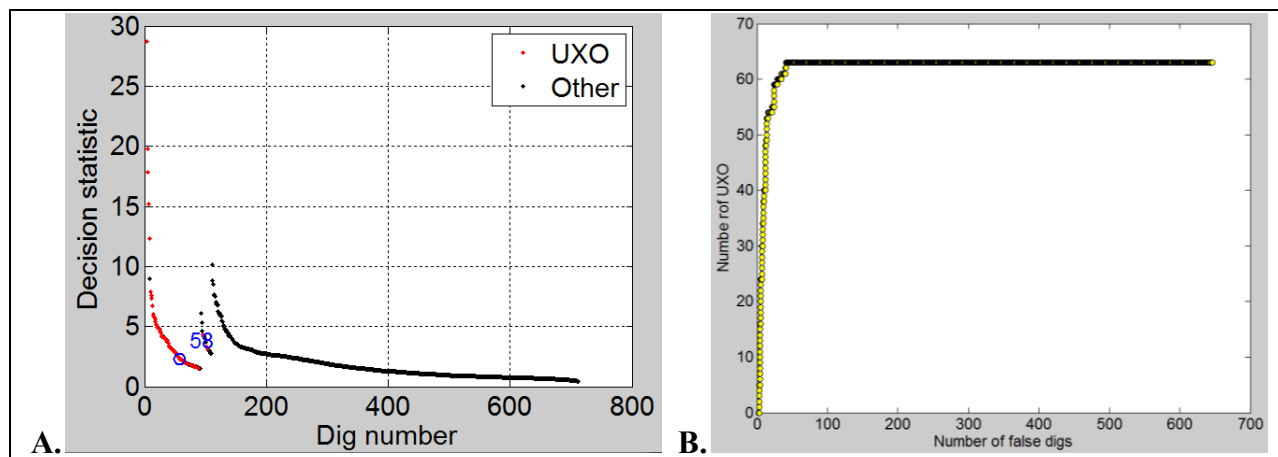


Figure 36: Decision statistic (A) based on "recognized UXO" (red dots) and expected ROC curve (B).

### 5. Stop-dig decision

A dig list is generated with the multi-stage classifier. The corresponding polarizabilities are visually inspected to verify that the classifier performs as expected and to gauge the relevance of the selected parameters – for instance obvious soil-like models may be selected by the classifier because they resemble a 37mm or 105 mm more than their associated clutter, in which case the model can be manually rejected. Training data are left among other anomalies to relate their associated polarizabilities to similar-ranked anomalies. The operator manually select a stop dig point after which UXO are less likely to appear.